The Nitrogen-Vacancy (NV) Center in Diamond

Dieter Suter
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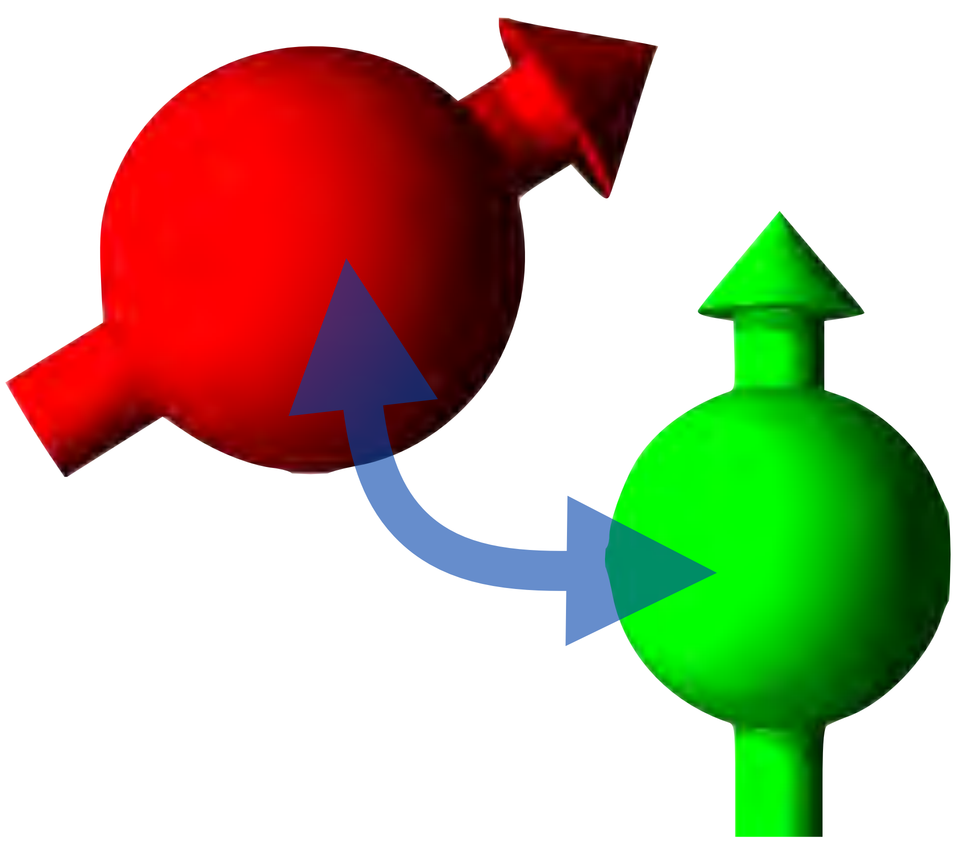
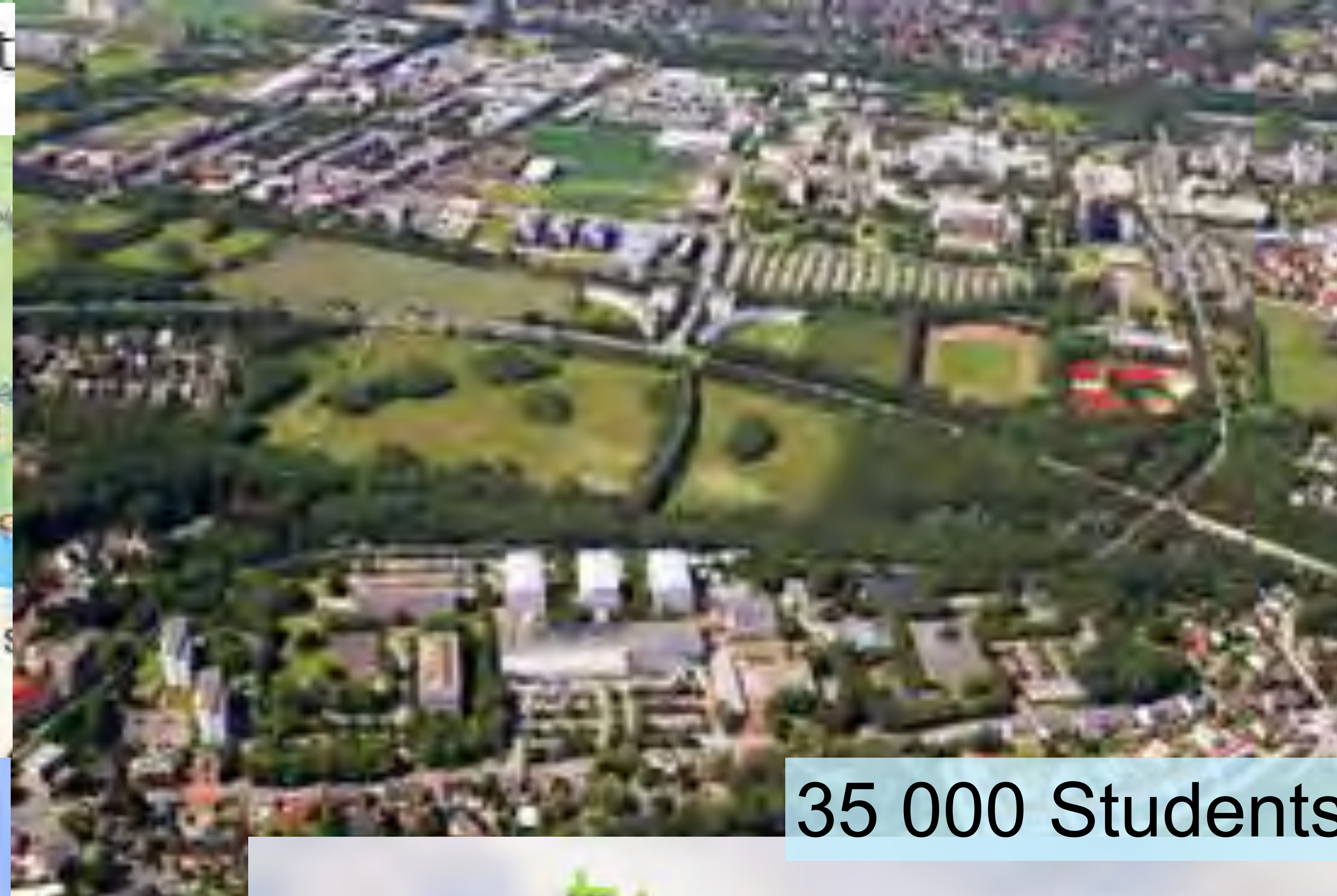


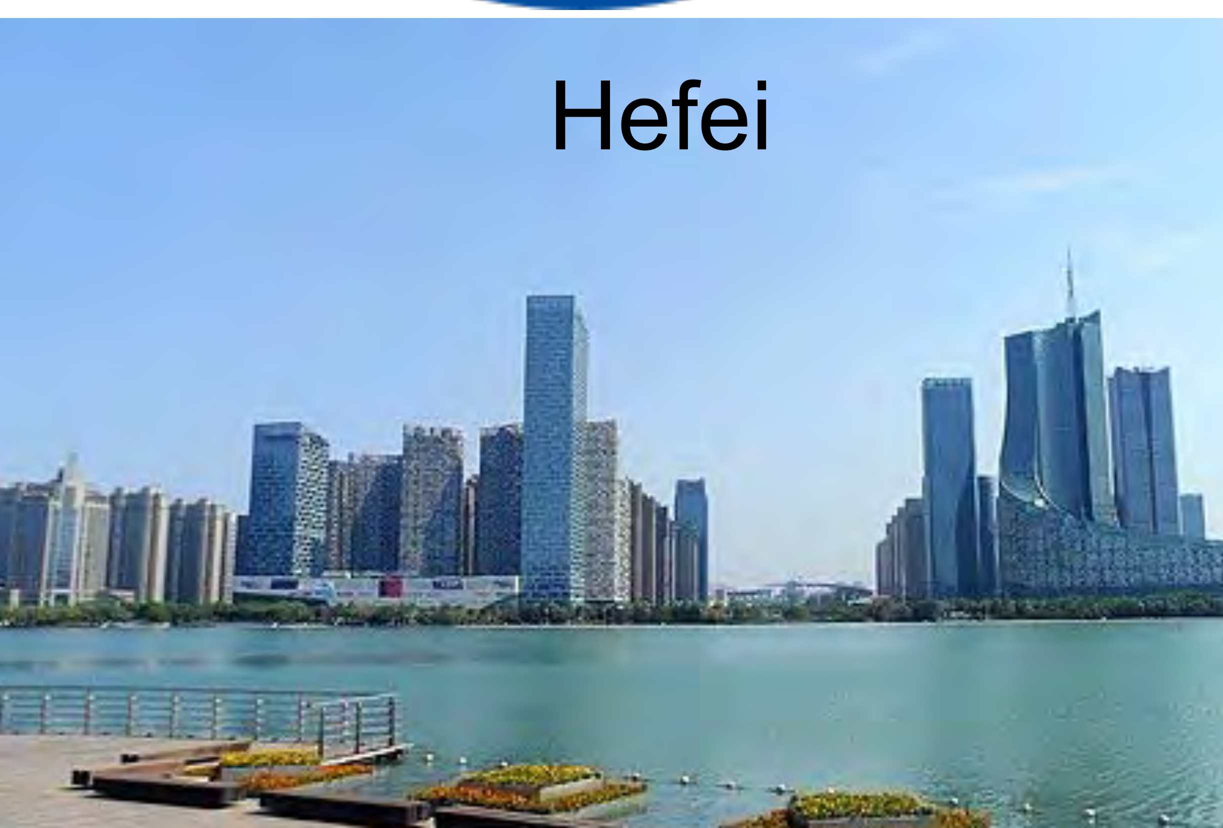
technische universität dortmund



35 000 Students

Dieter Suter
University of Science and Technology of China

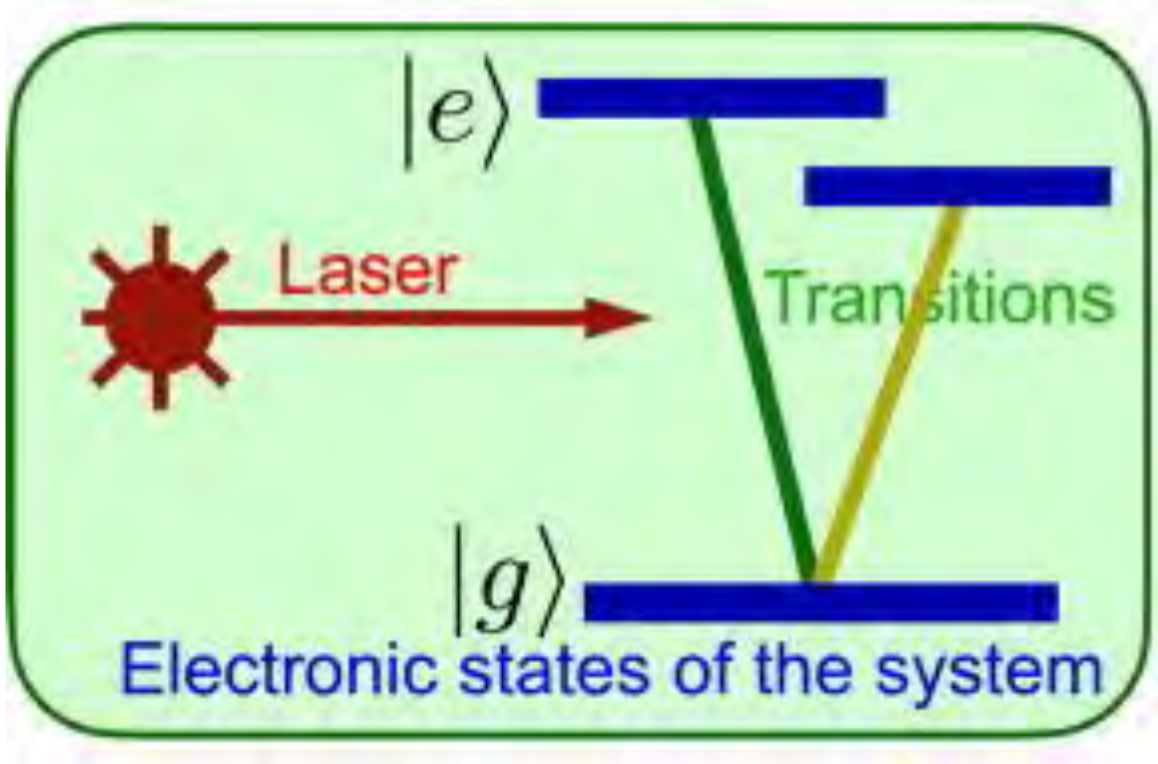
Students	16,718
Undergraduates	7,426
Postgraduates	9,292



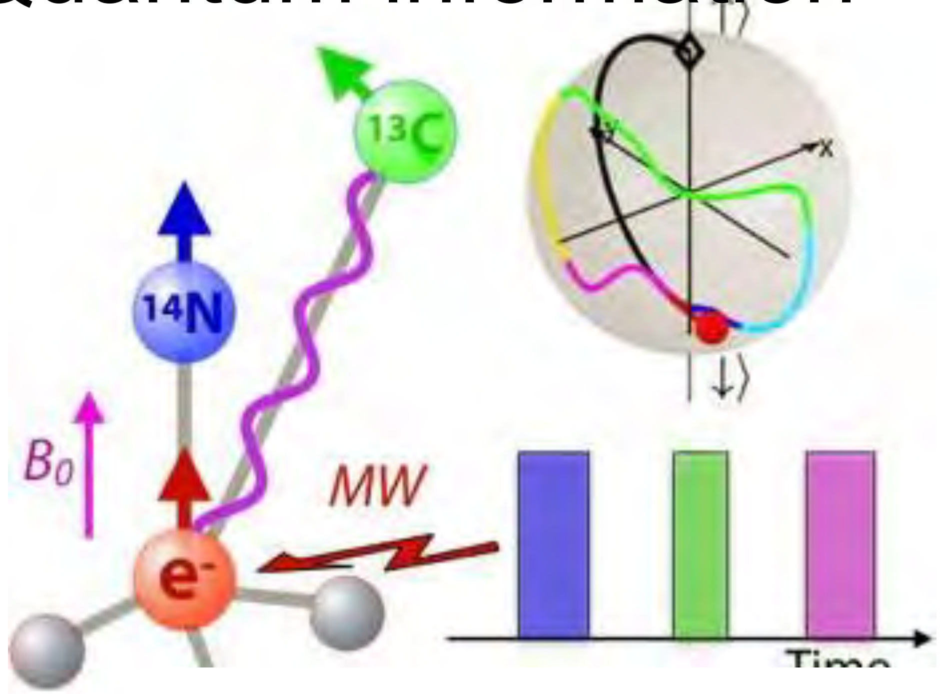
Research Fields

Magnetic resonance

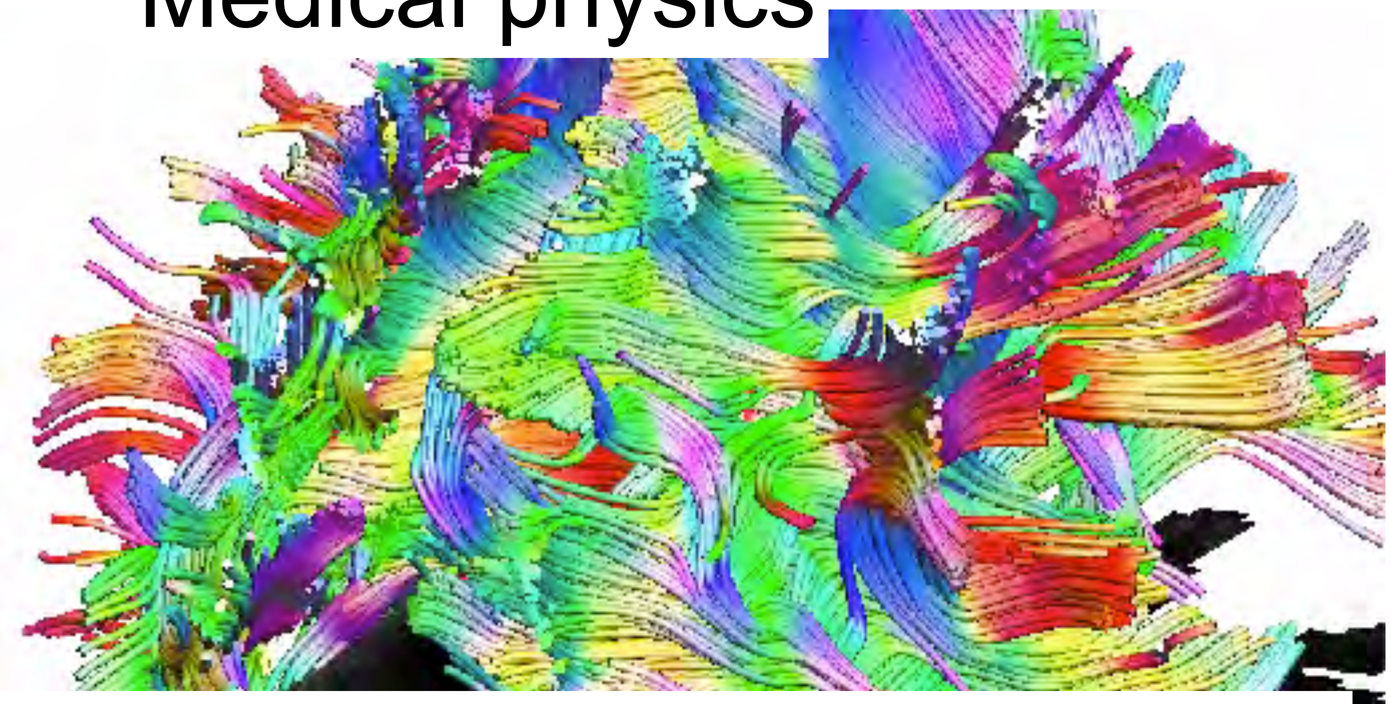
Laser spectroscopy



Quantum information

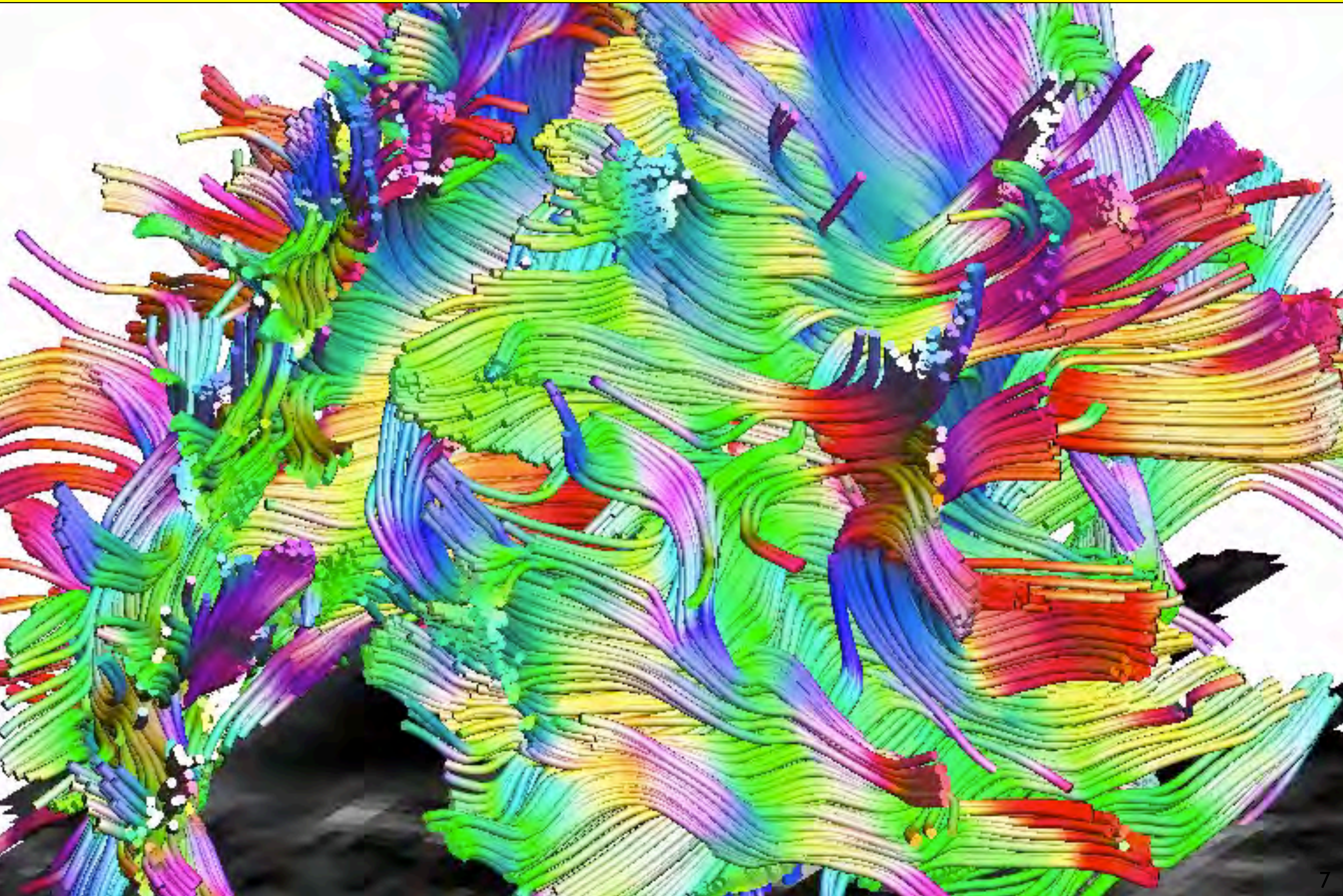


Medical physics



https://ag-suter.physik.tu-dortmund.de/research-interests/

NMR Meets Biology (and Medicine)

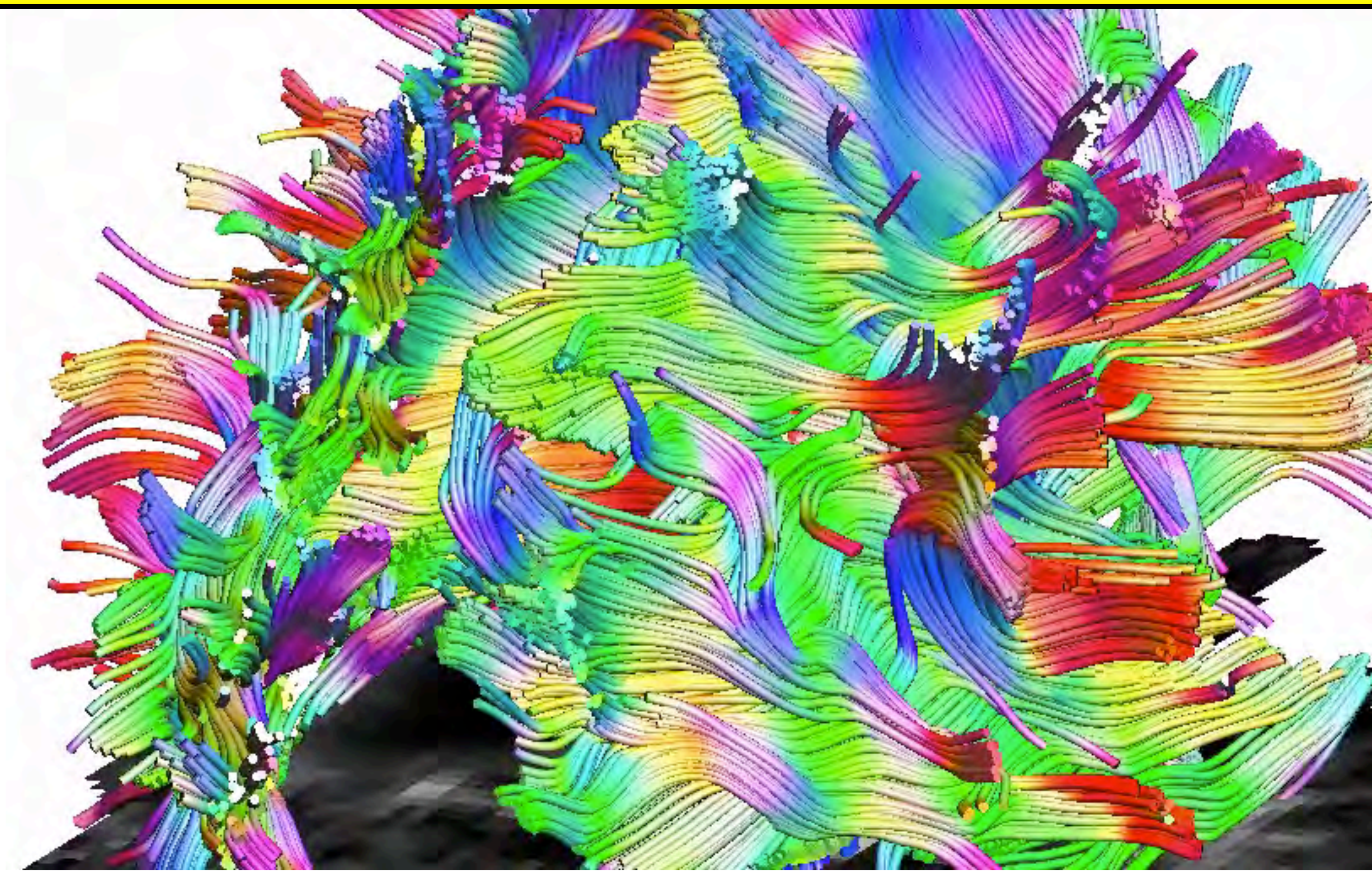


Human Brain

~ 10^{11} nerve cells

~ $3 \cdot 10^9$ m fibers

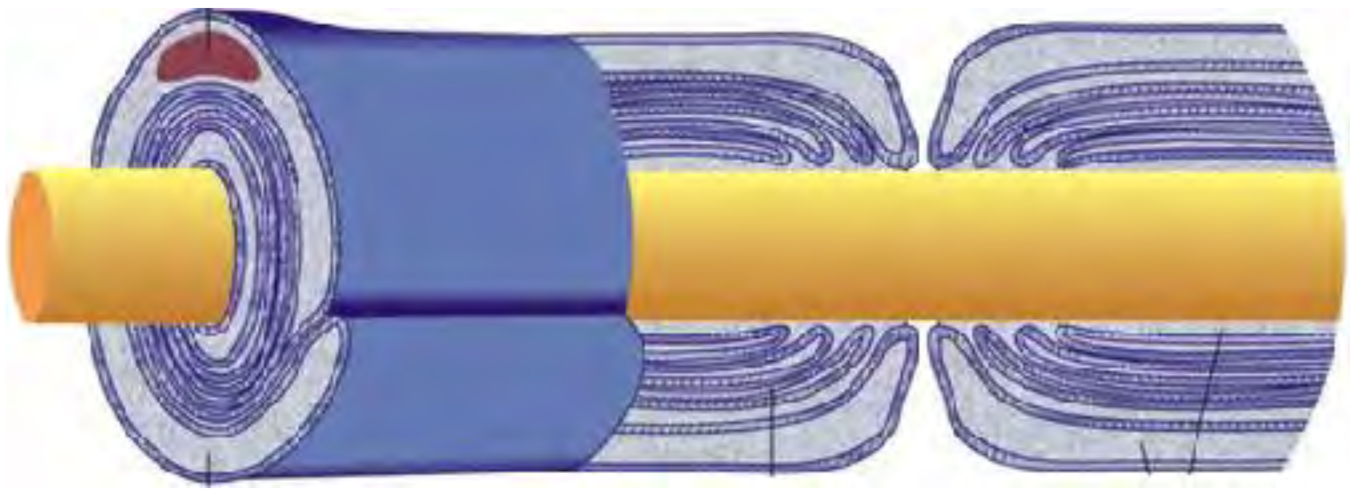
cannot image single fibers



but: NMR can measure the average orientation of bundles of nerve cells!

Anisotropic Diffusion

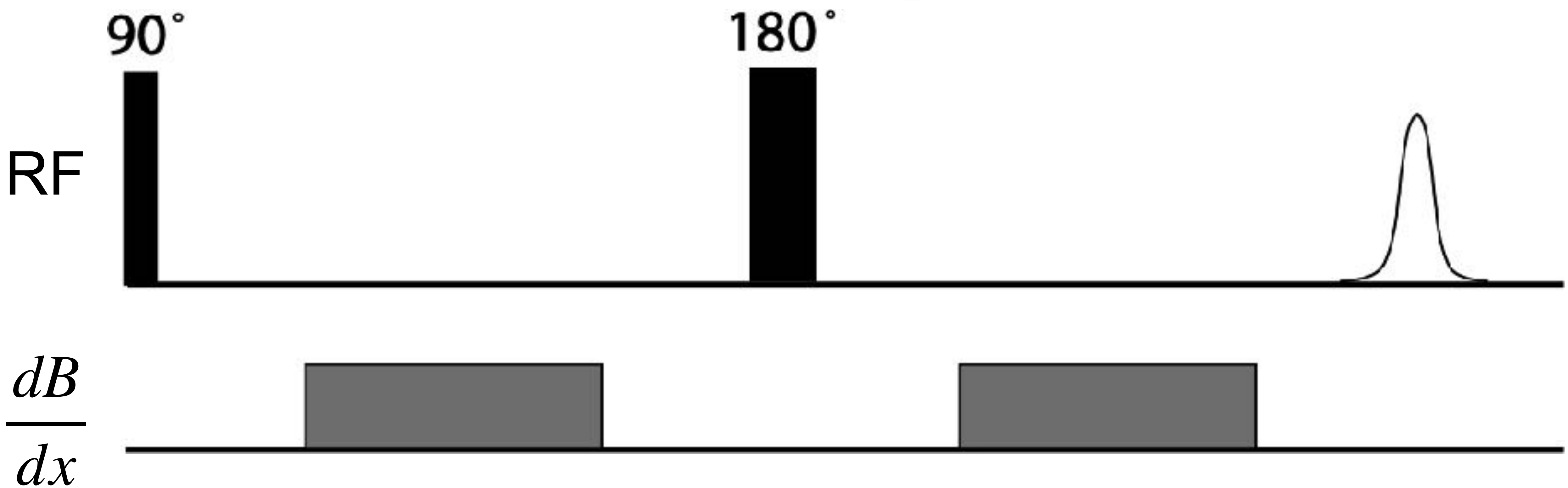
Axon



Length : cm
Diameter : 10 μm

→ Diffusion || axis ≫ Diffusion ⊥ axis

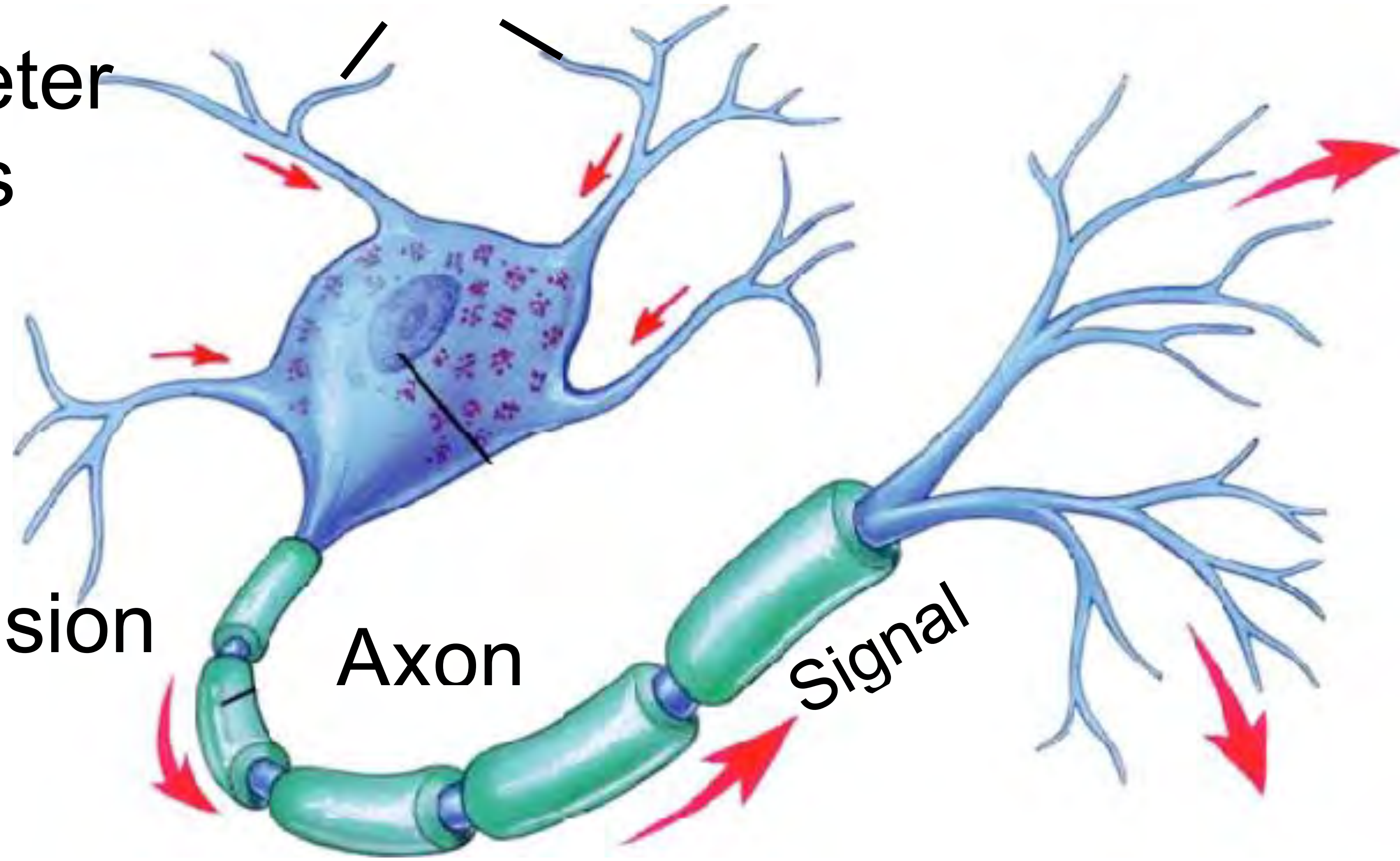
Measure $\langle x(o)x(t) \rangle$ → Diffusion tensor



E. O. Stejskal and J. E. Tanner, J. Chem. Phys. 42, 288-292 (1965).

Limits on Precision

Example : measure diameter and orientation of neurons



Quantum sensing:
Measurement process determines ultimate precision

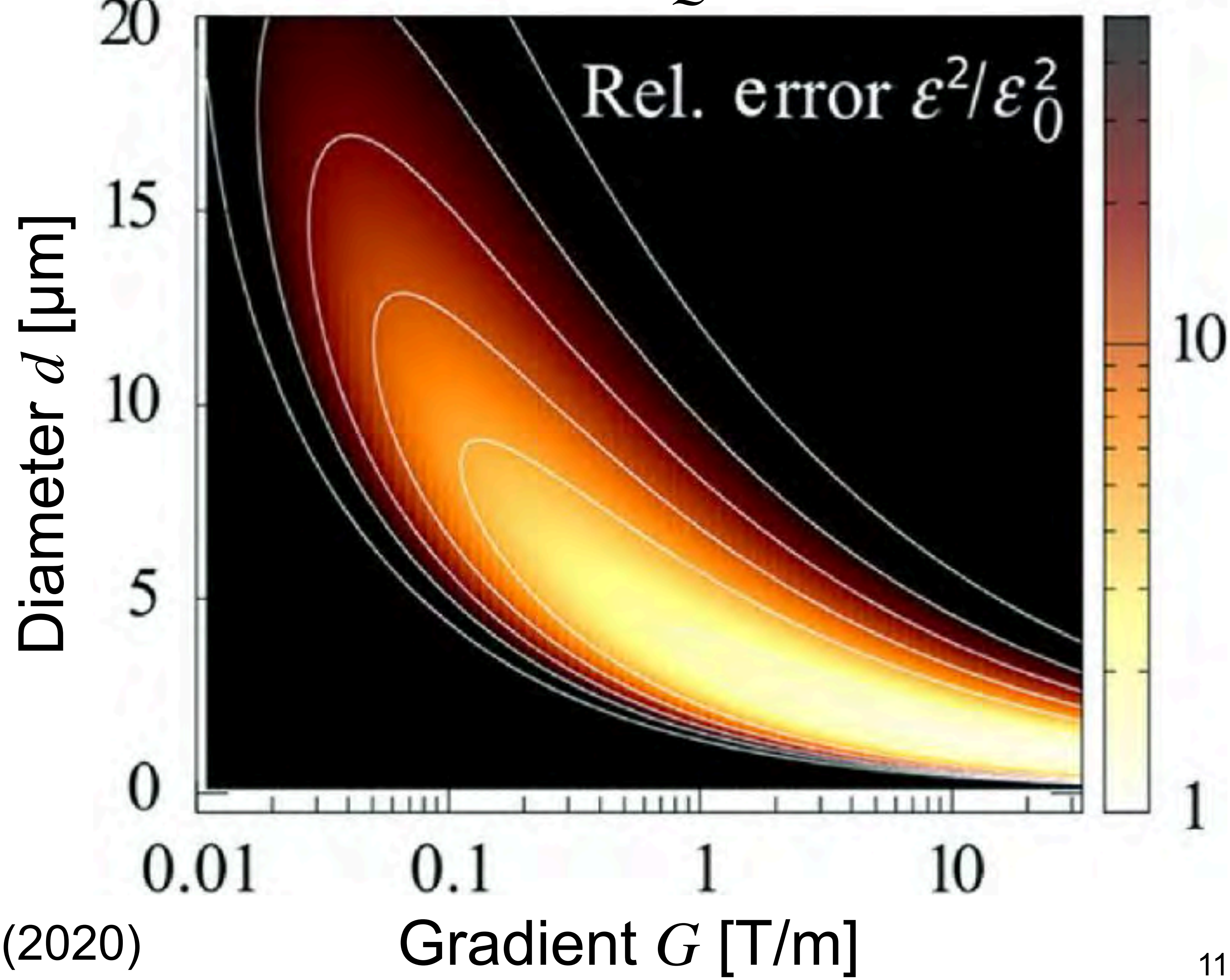
Quantum Cramér-Rao bound $(\Delta\theta)^2 \geq \dfrac{1}{mF_Q}$

Quantum Fisher information $F_Q = 2\sum \dfrac{(\lambda_k - \lambda_l)^2}{\lambda_k + \lambda_l} |\langle k|A|l\rangle|^2$

Limits on Precision

Quantum Cramér-Rao bound $(\Delta\theta)^2 \geq \frac{1}{mF_Q}$

Optimal control parameters

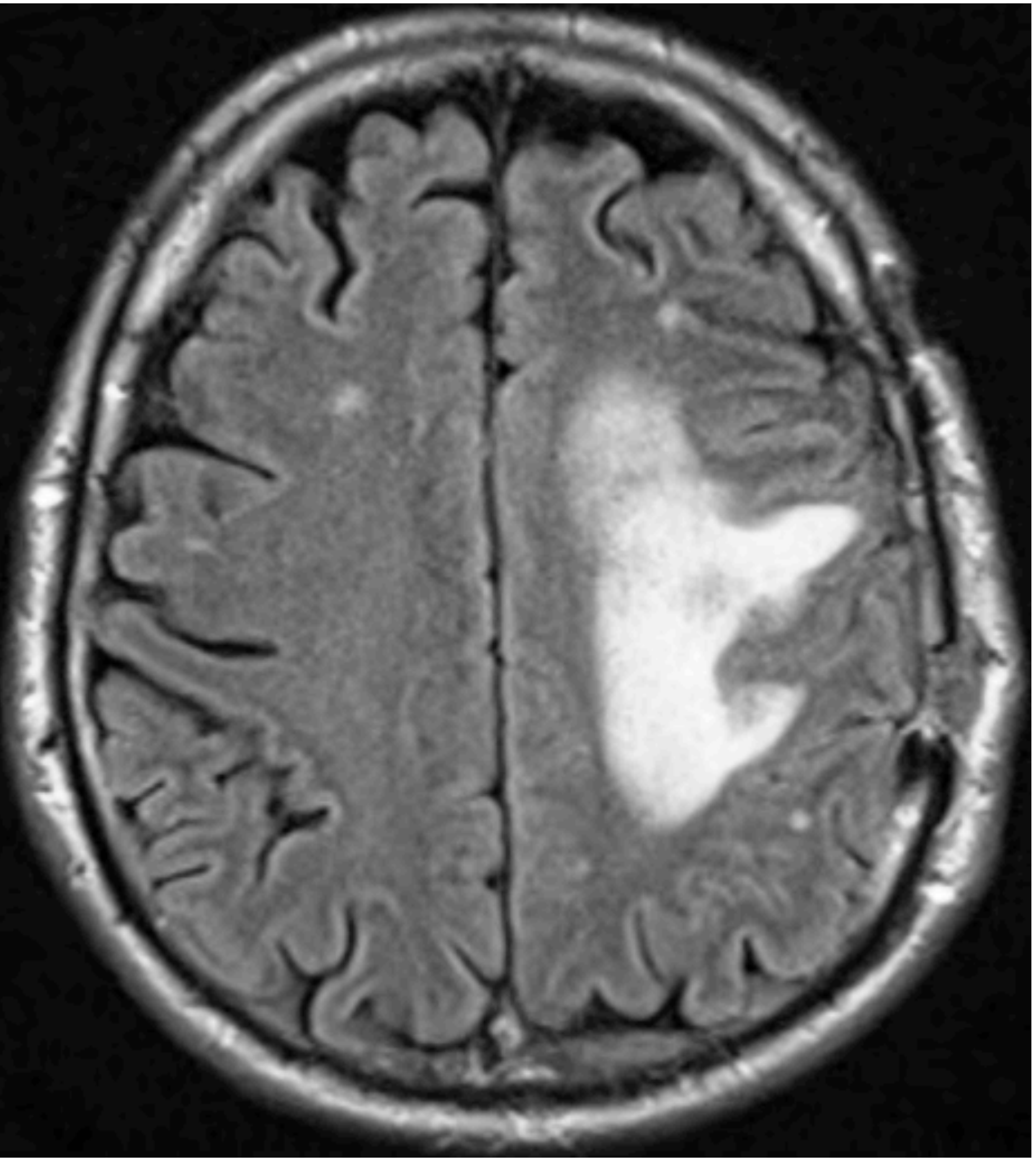


Quantum limits on diffusion-weighted measurements

PR Applied 14, 024088 (2020)

Quantification of Brain Tumours

Glioma



Early detection and identification is essential for successful treatment and survival

Choices:

- Pulse sequence
- Contrast
- Data analysis

Z. Med. Physik 28, 14 - 24 (2018).

Spectroscopic Imaging

Distribution of metabolites in the human body can assist identification of disease and treatment

The concentration of metabolites is tiny compared to H_2O

Spectroscopic Imaging

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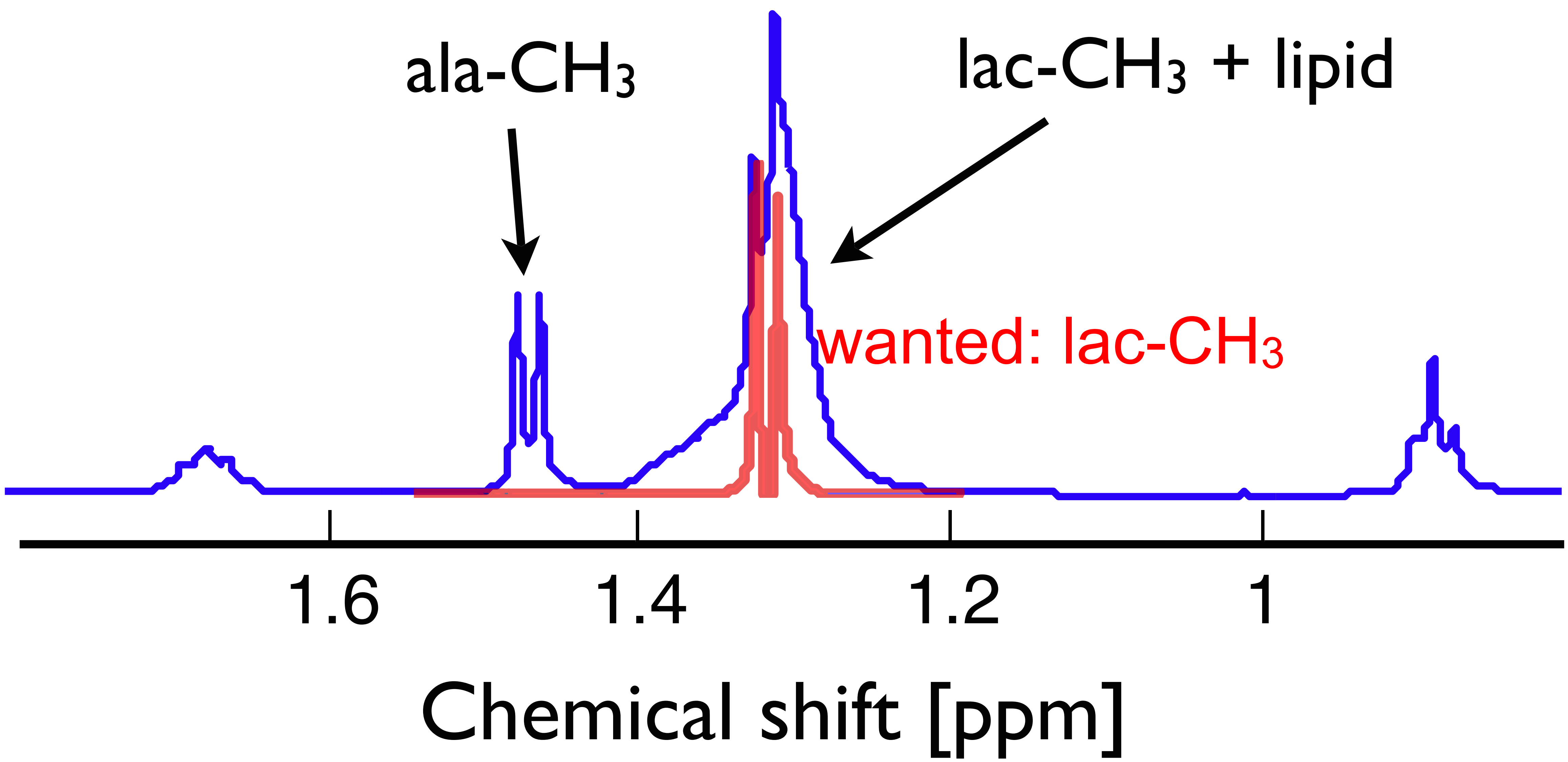
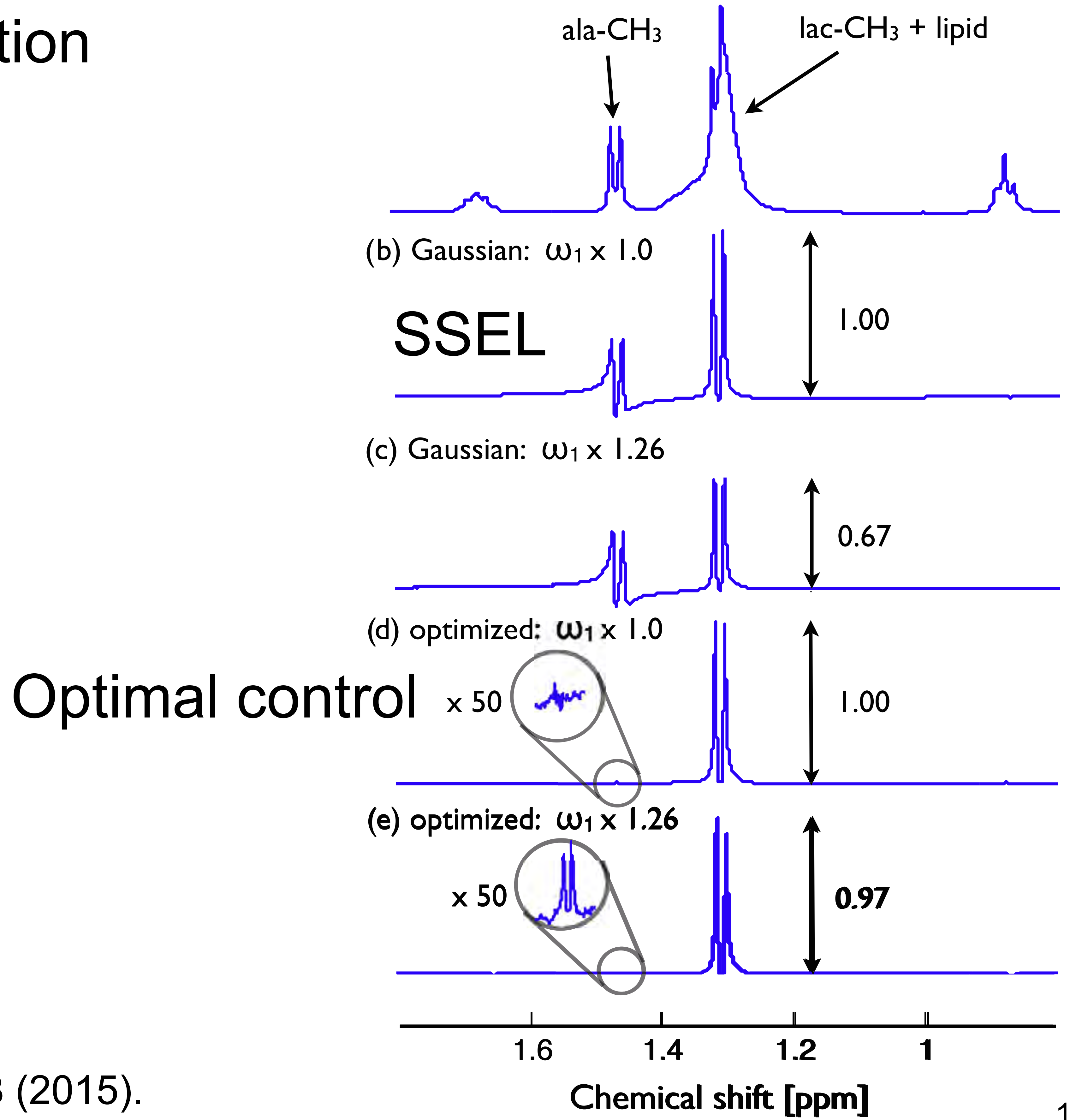
→ Selective excitation and detection



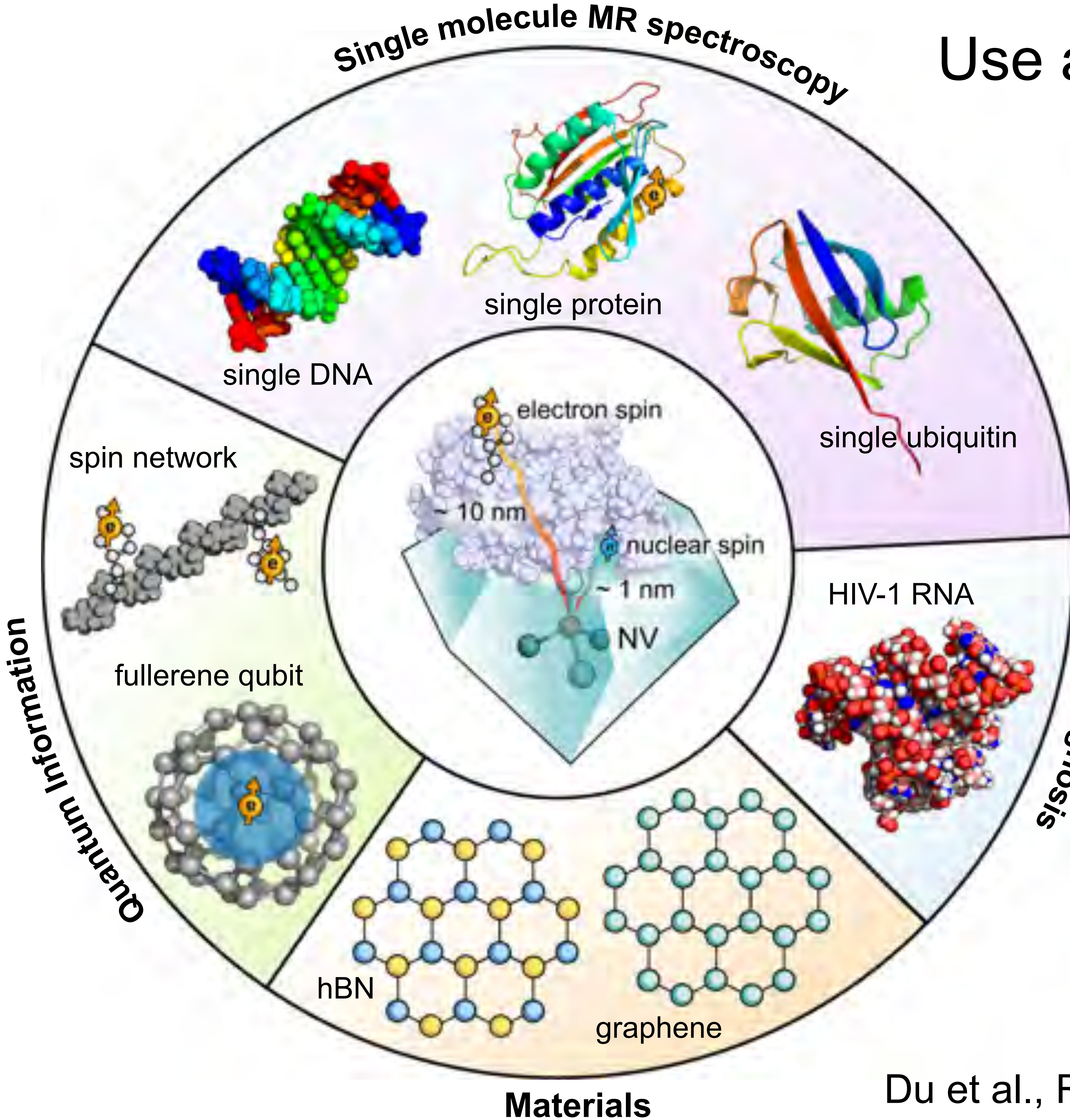
Spectroscopic Imaging

Selective excitation and detection

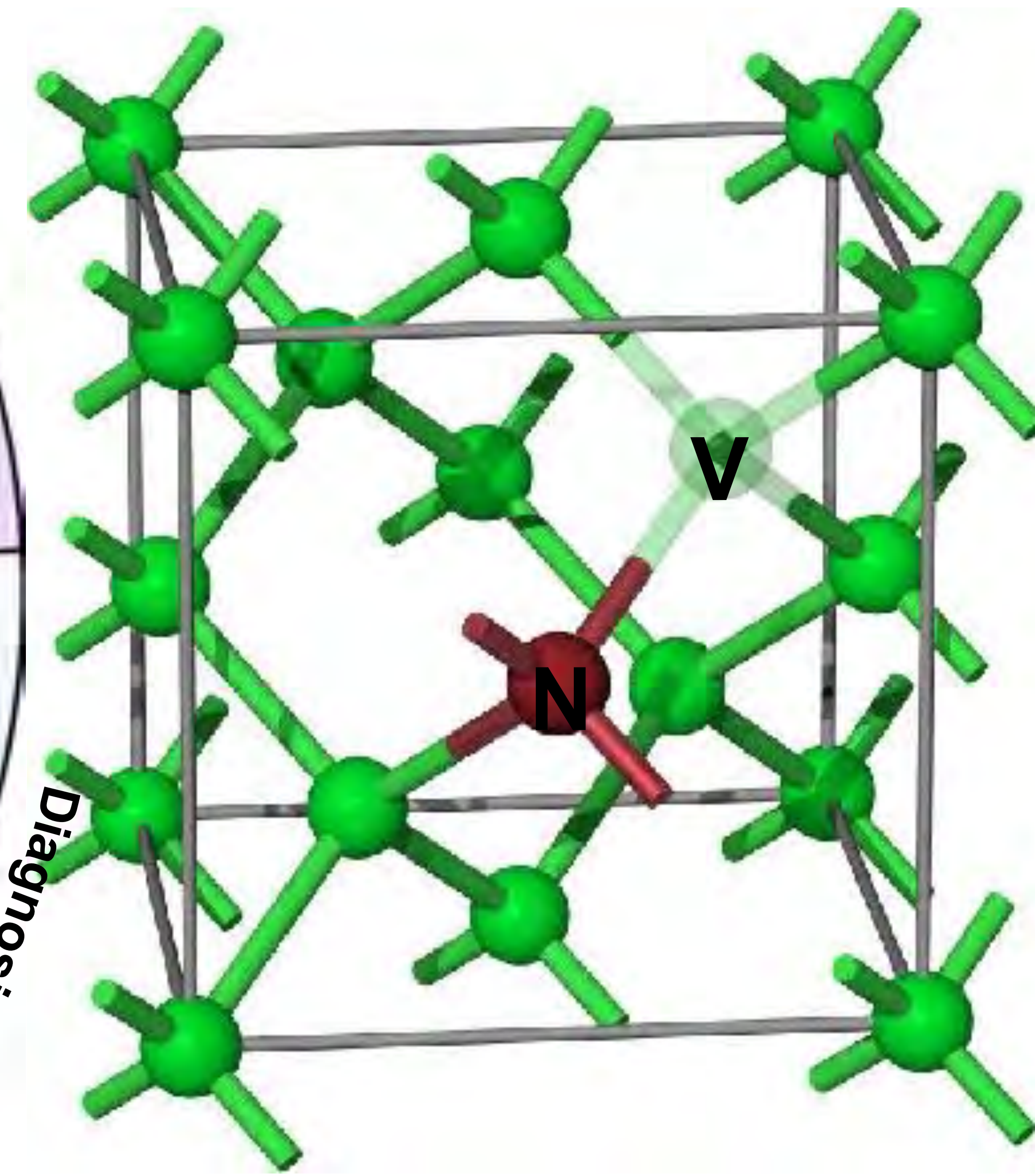


JMR 243, 8-16 (2014); 255, 34-38 (2015).

Atomic Resolution?

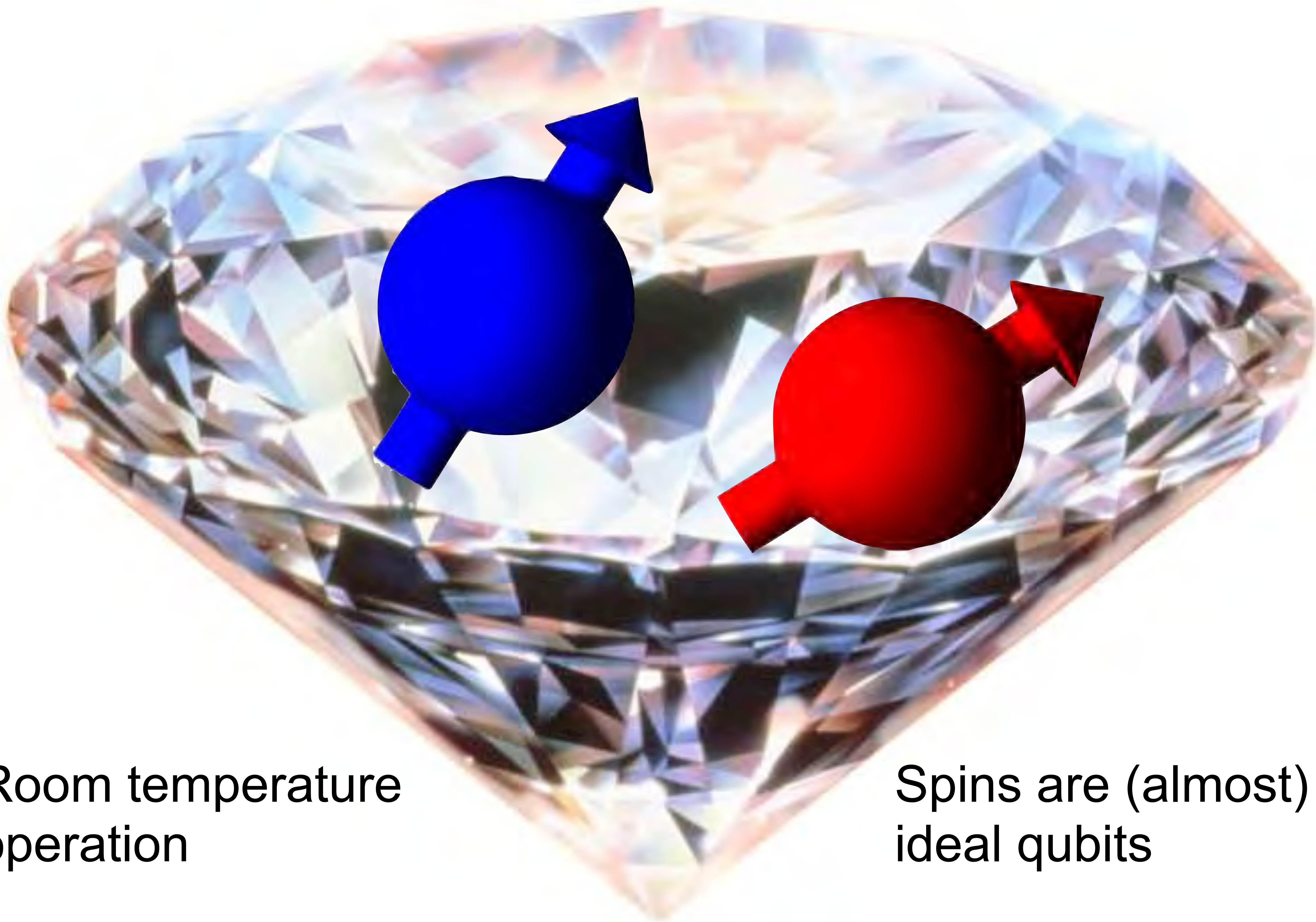


Use an atomic-size sensor (single spin)



Du et al., Rev. Mod. Phys. 96, 025001 (2024).

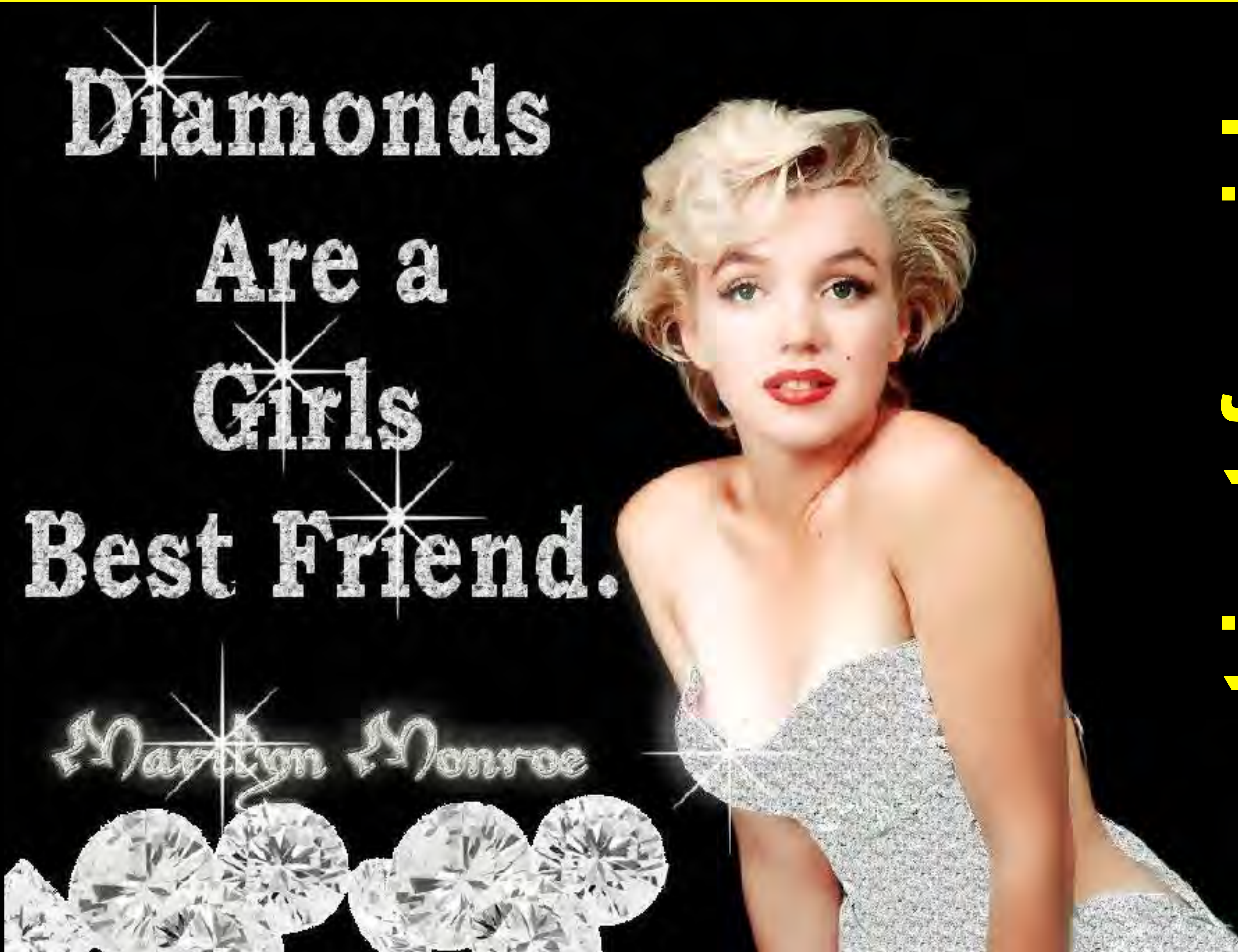
Spins in Diamond



Room temperature operation

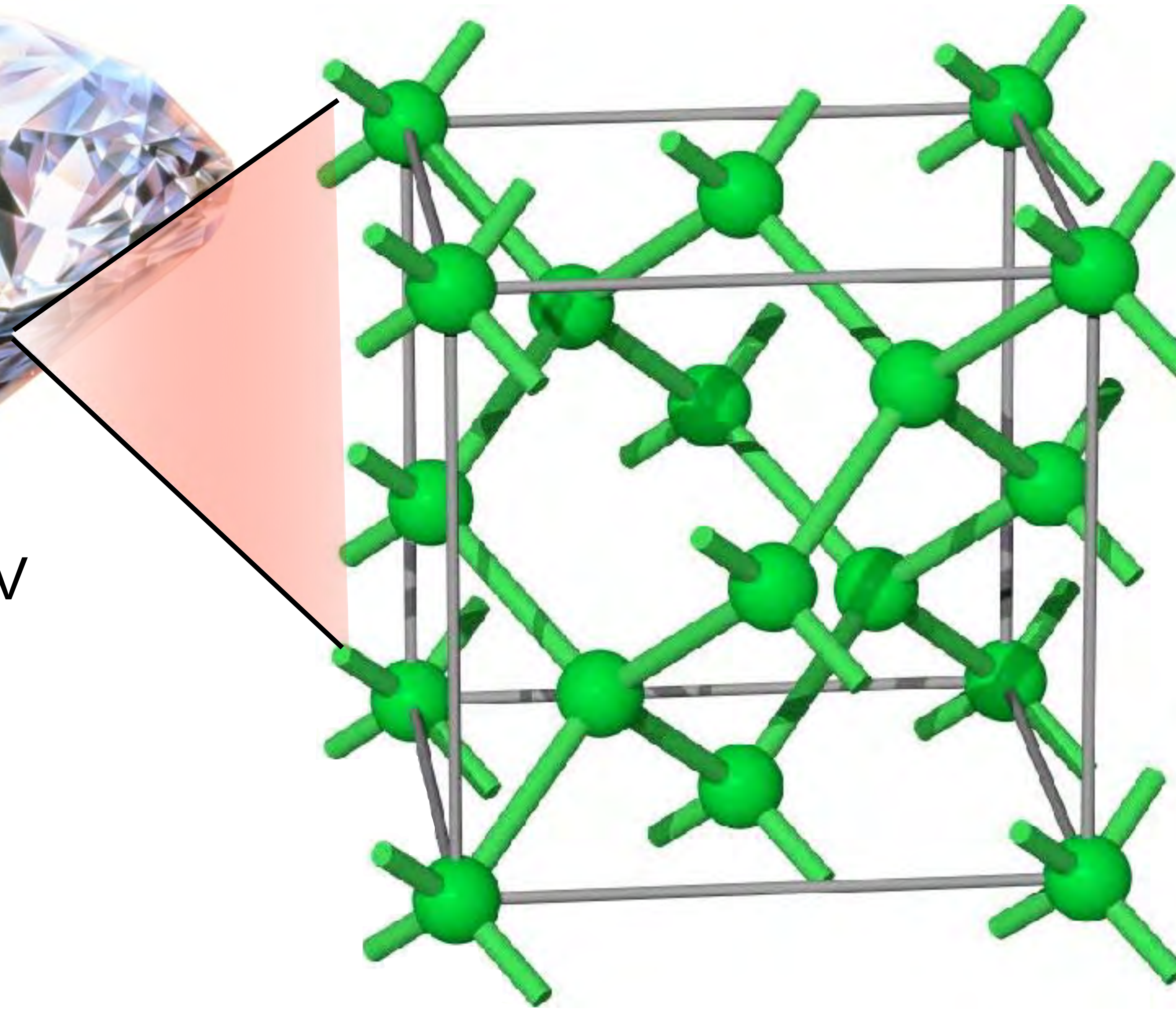
Spins are (almost) ideal qubits

Diamonds



not just for girls

Diamond



Band gap ~5.5 eV
→ transparent

Color Centers

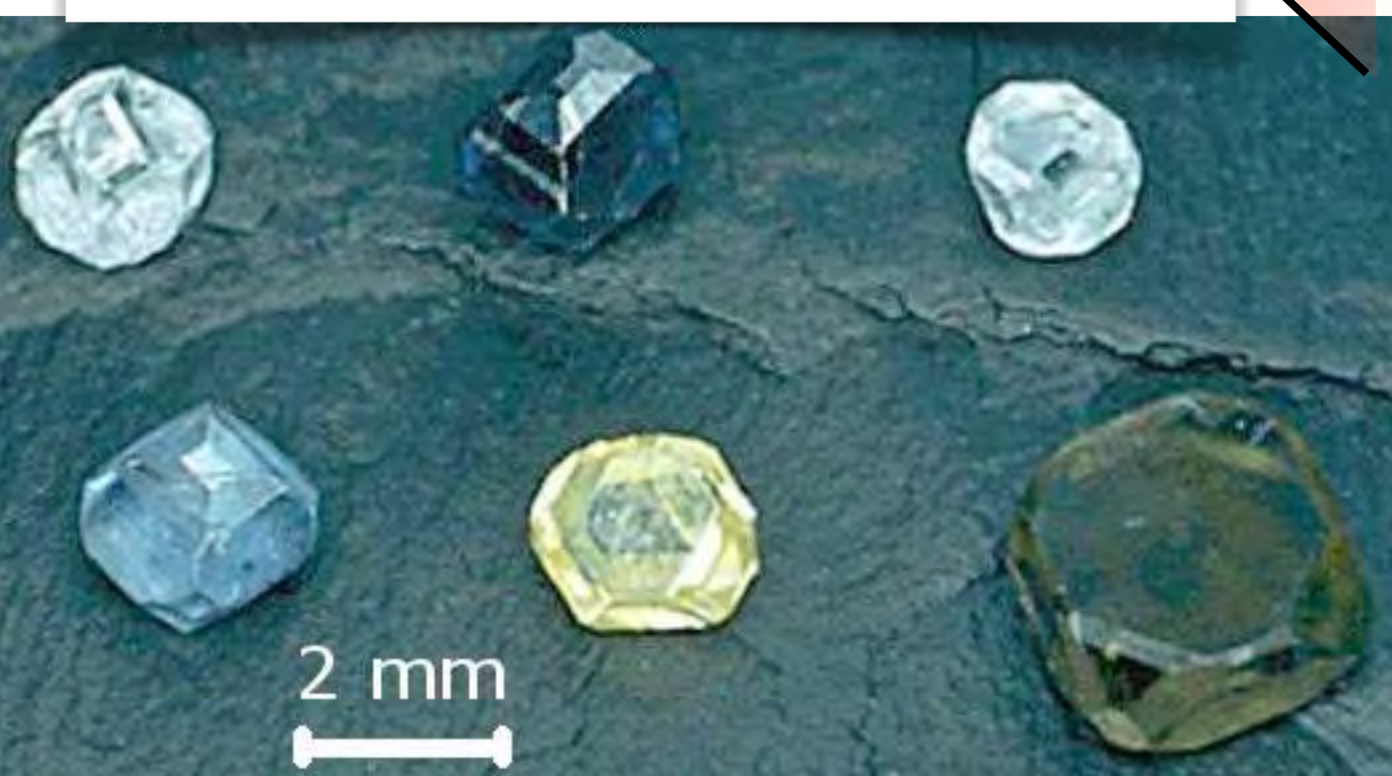
Nitrogen: yellow-orange

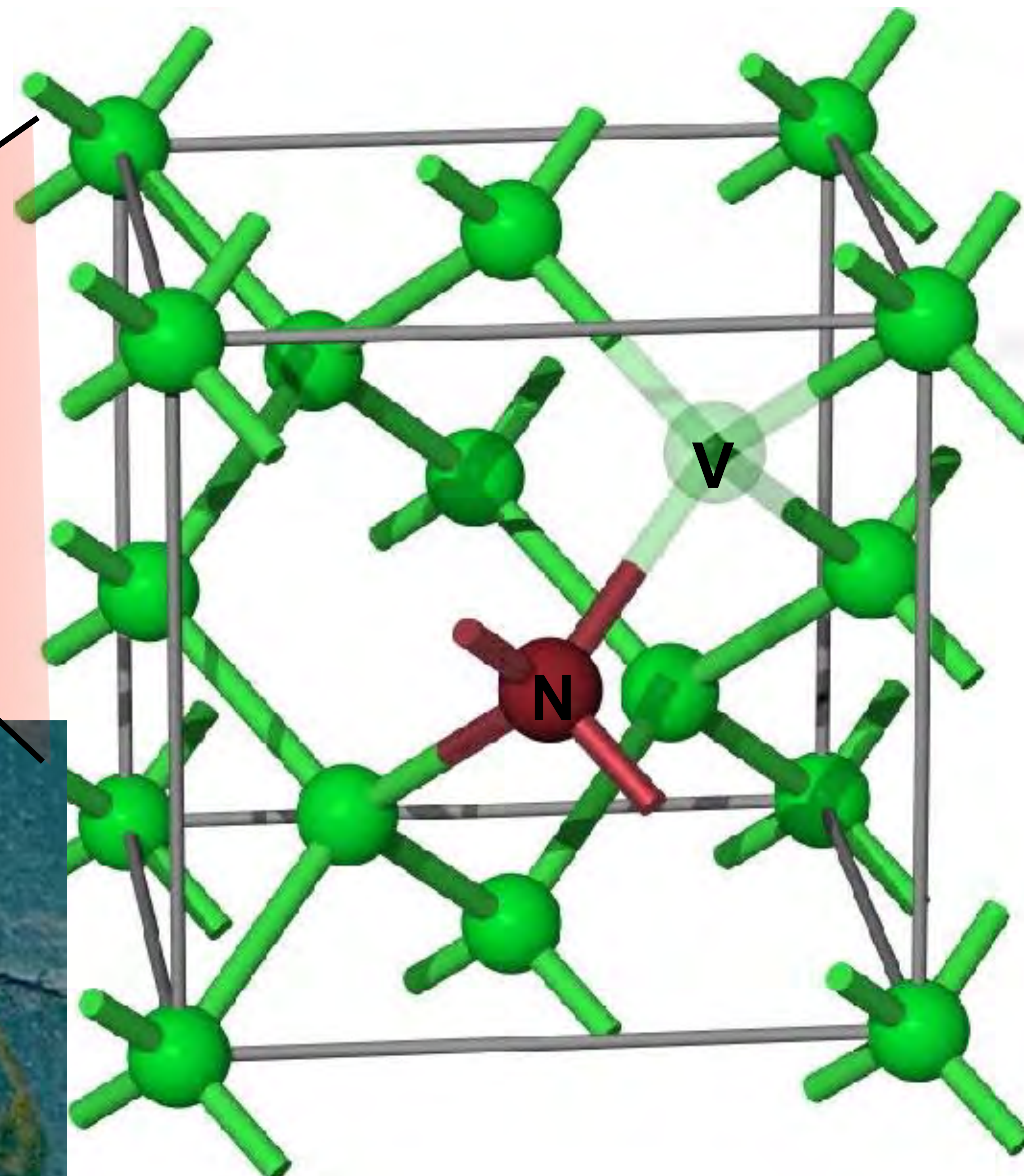
Boron: blue

Defects make diamonds valuable and interesting!

Diamond Nitrogen-Vacancy (NV)

Defects make diamonds valuable and interesting!



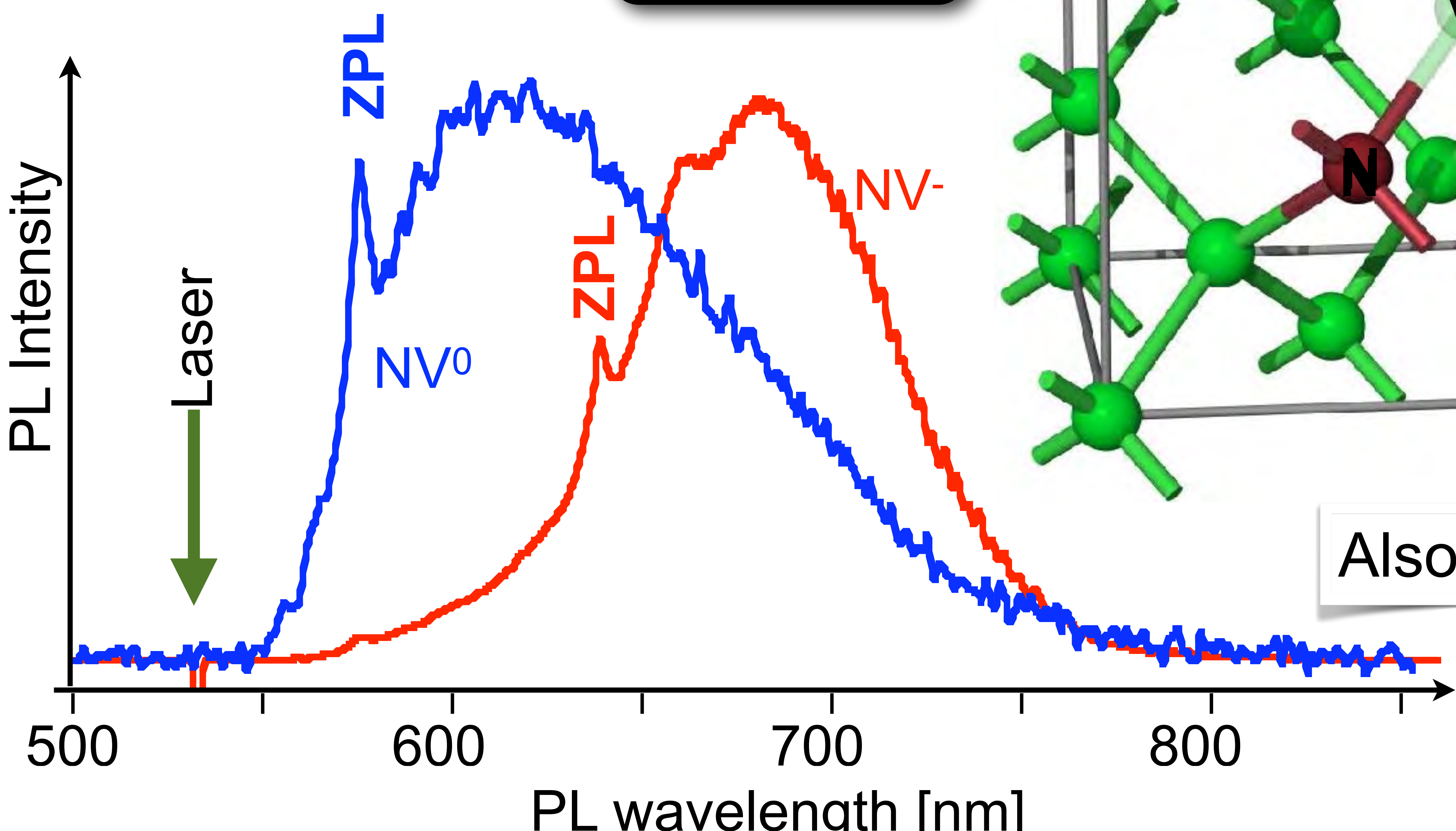


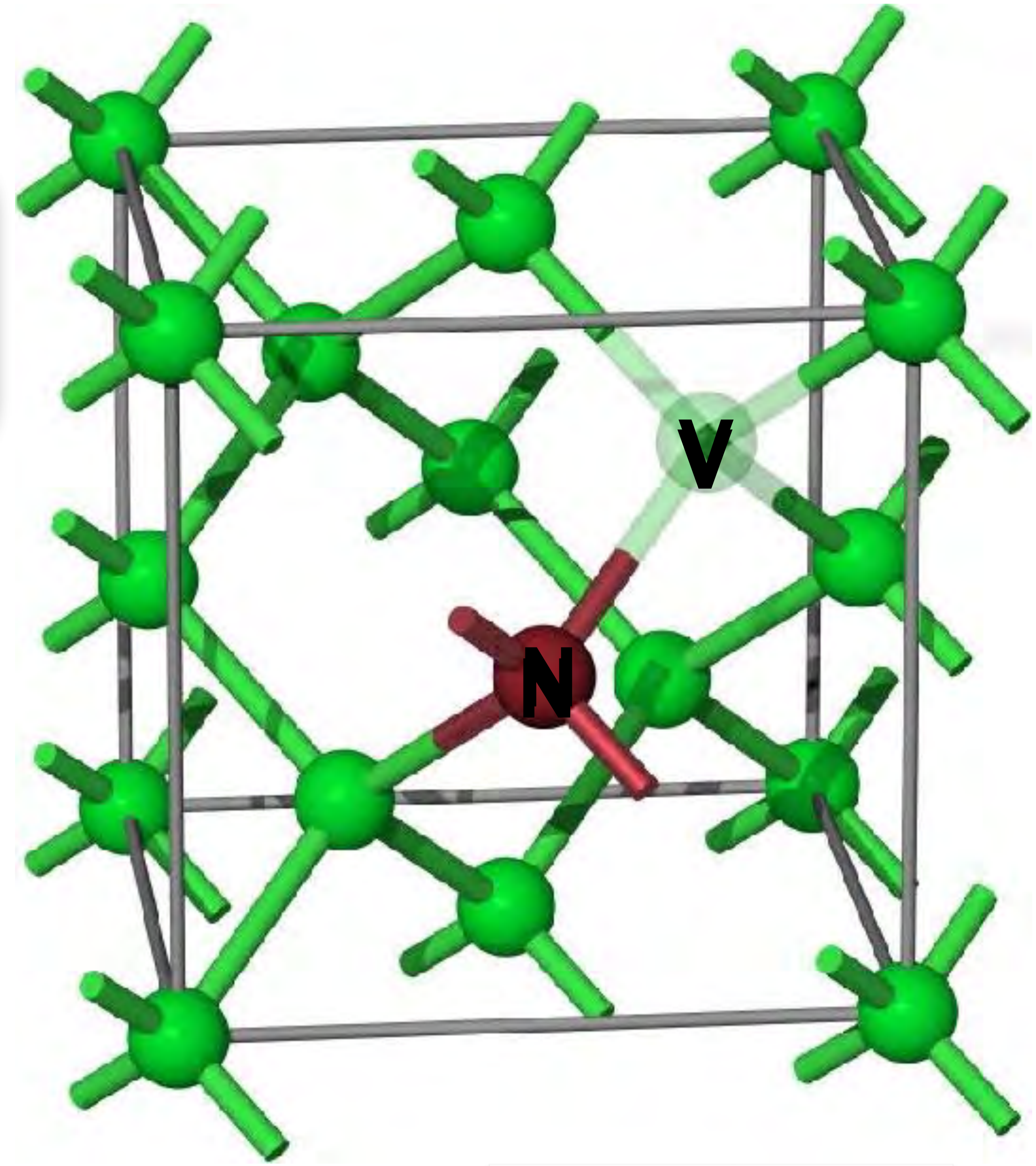
Optical Properties

possible charge states

5 electrons
spin 1/2

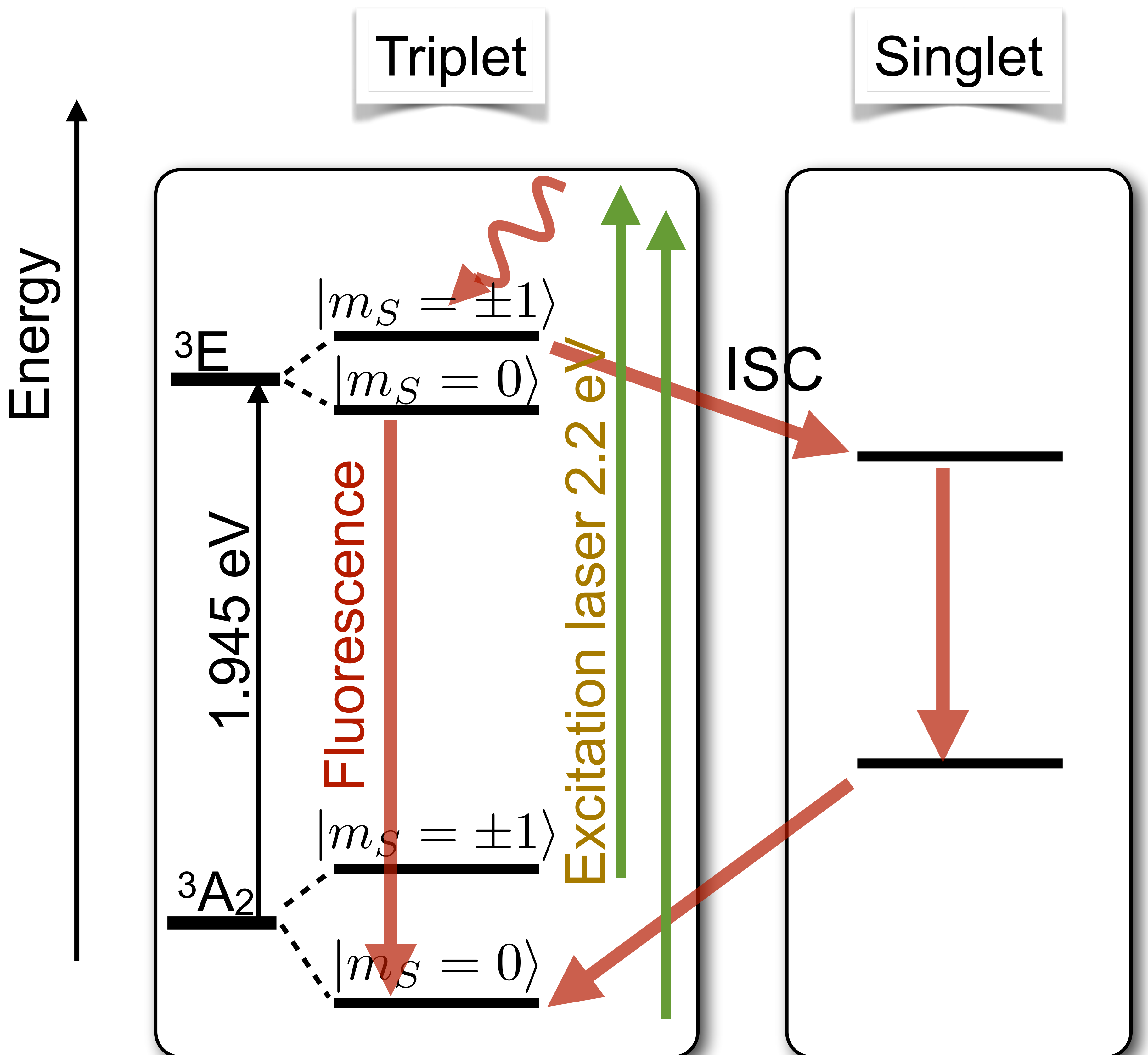
6 electrons
spin 1





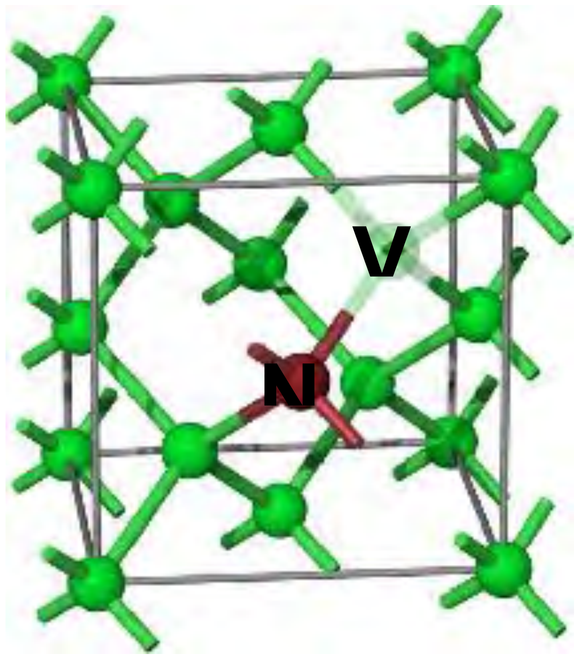
Also : NV^+

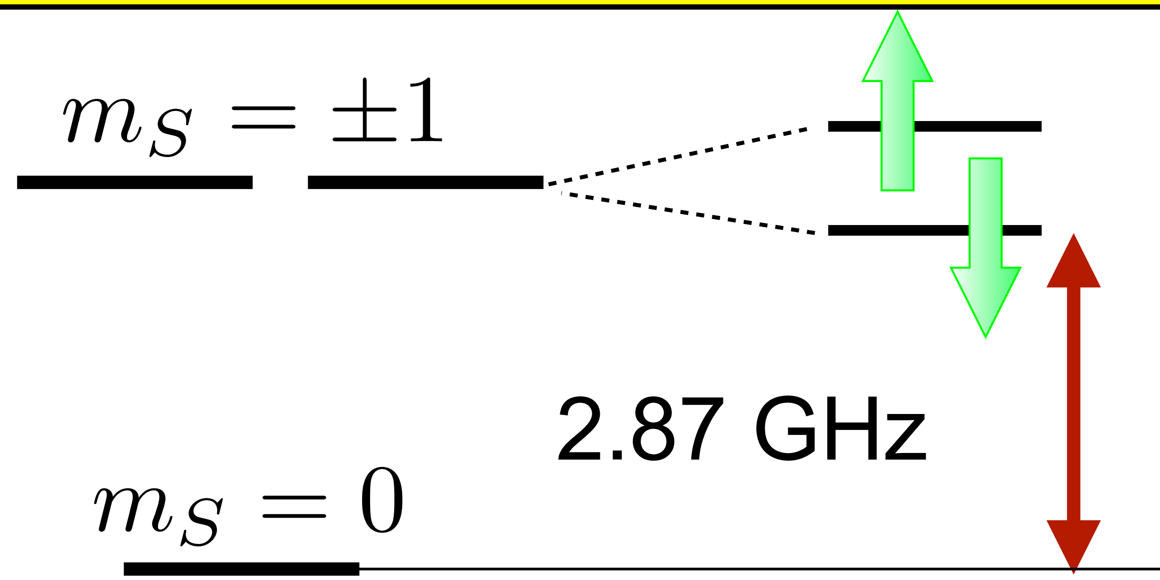
NV Centers : Optical Excitation



Laser initializes system into m_S=0 state

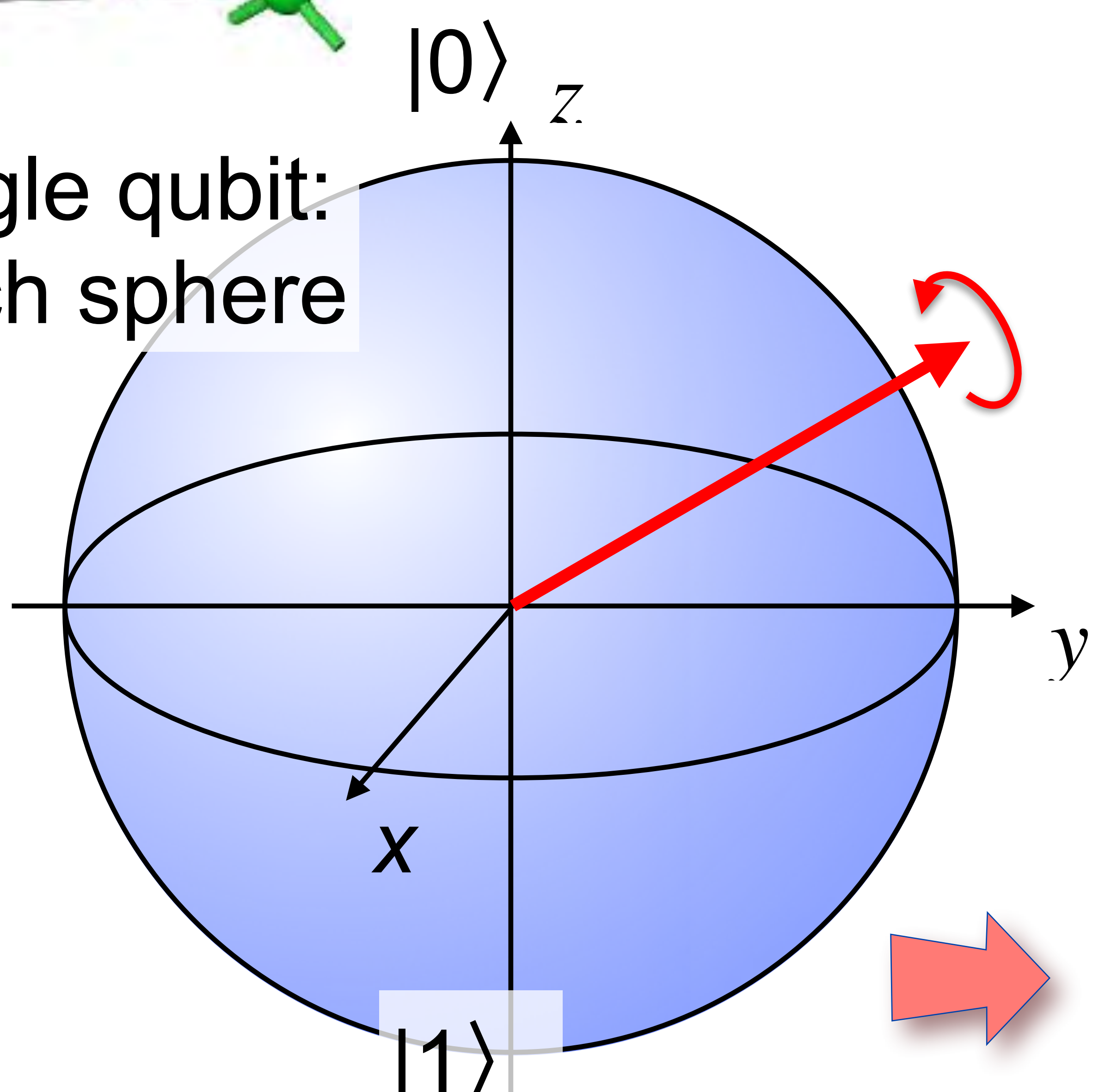
Gates: Electron Spin





Apply resonant MW pulse(s)

Single qubit: Bloch sphere



Pulse generates rotation on Bloch sphere

Parameters: Frequency, amplitude, phase, duration

Controls: orientation of rotation axis, rotation angle

Arbitrary single-qubit gates

Measuring with Quanta

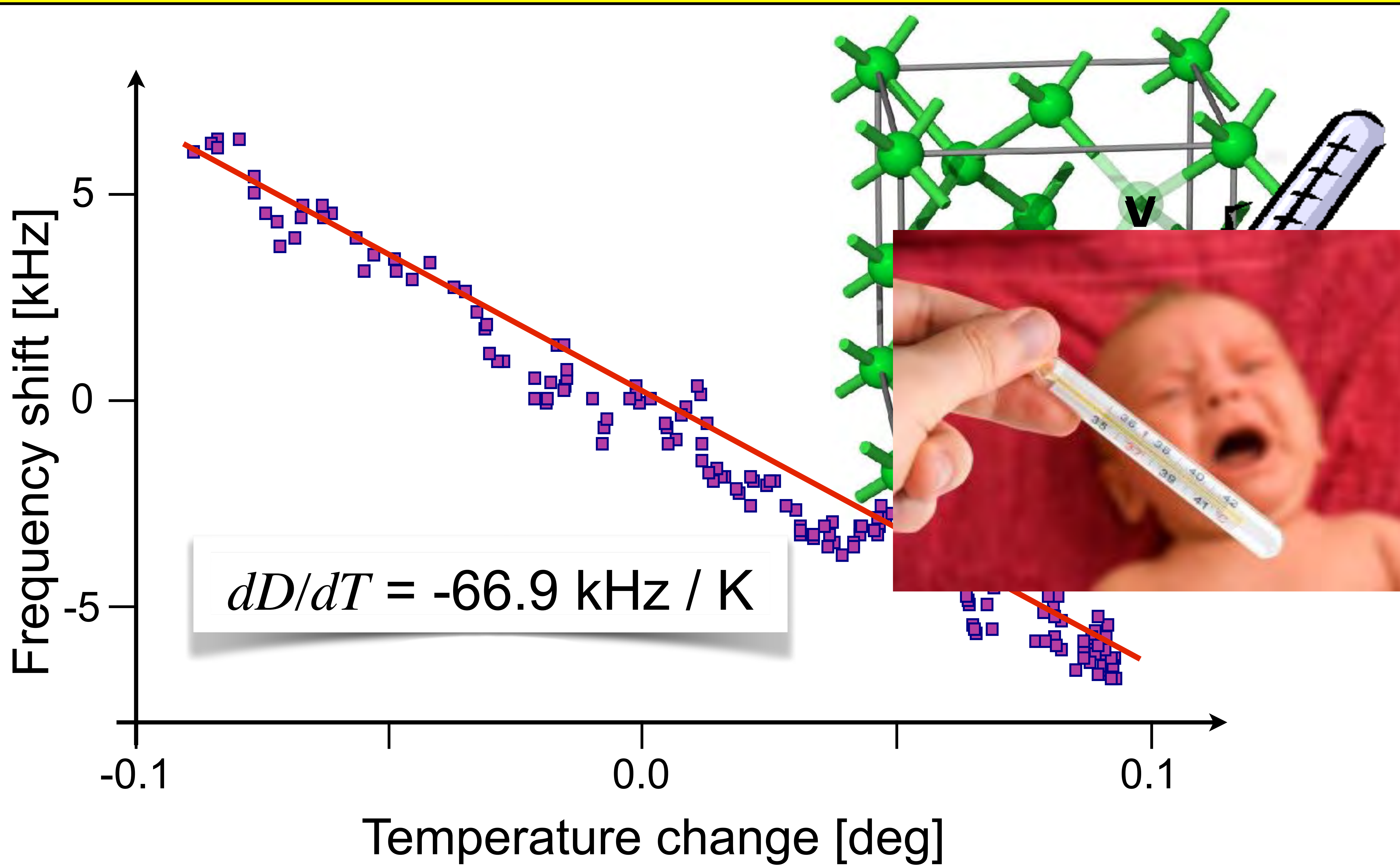
Quantum systems are at the basis of many high-precision measurements

Time

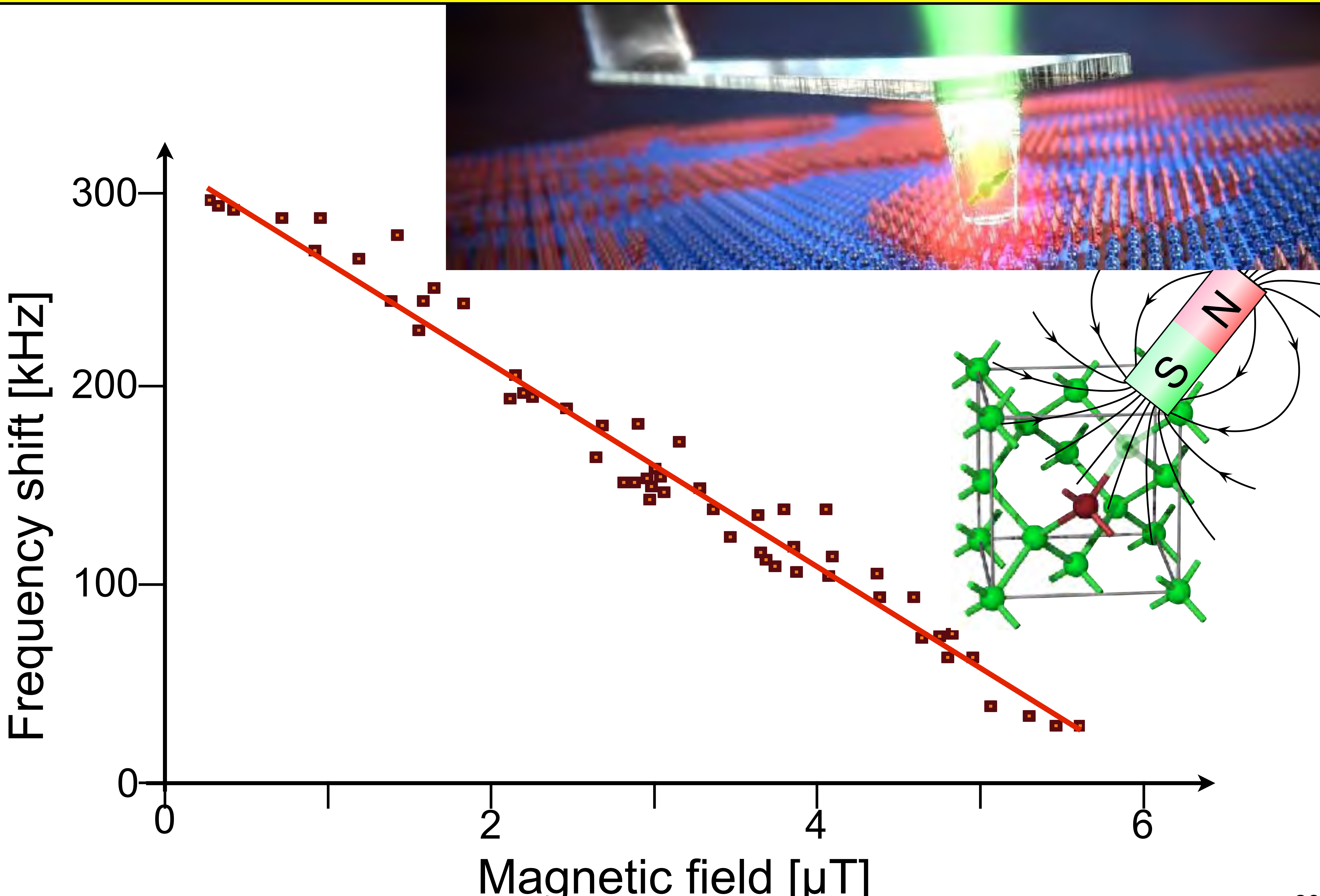
Magnetic field

Temperature

Single Atom Thermometer

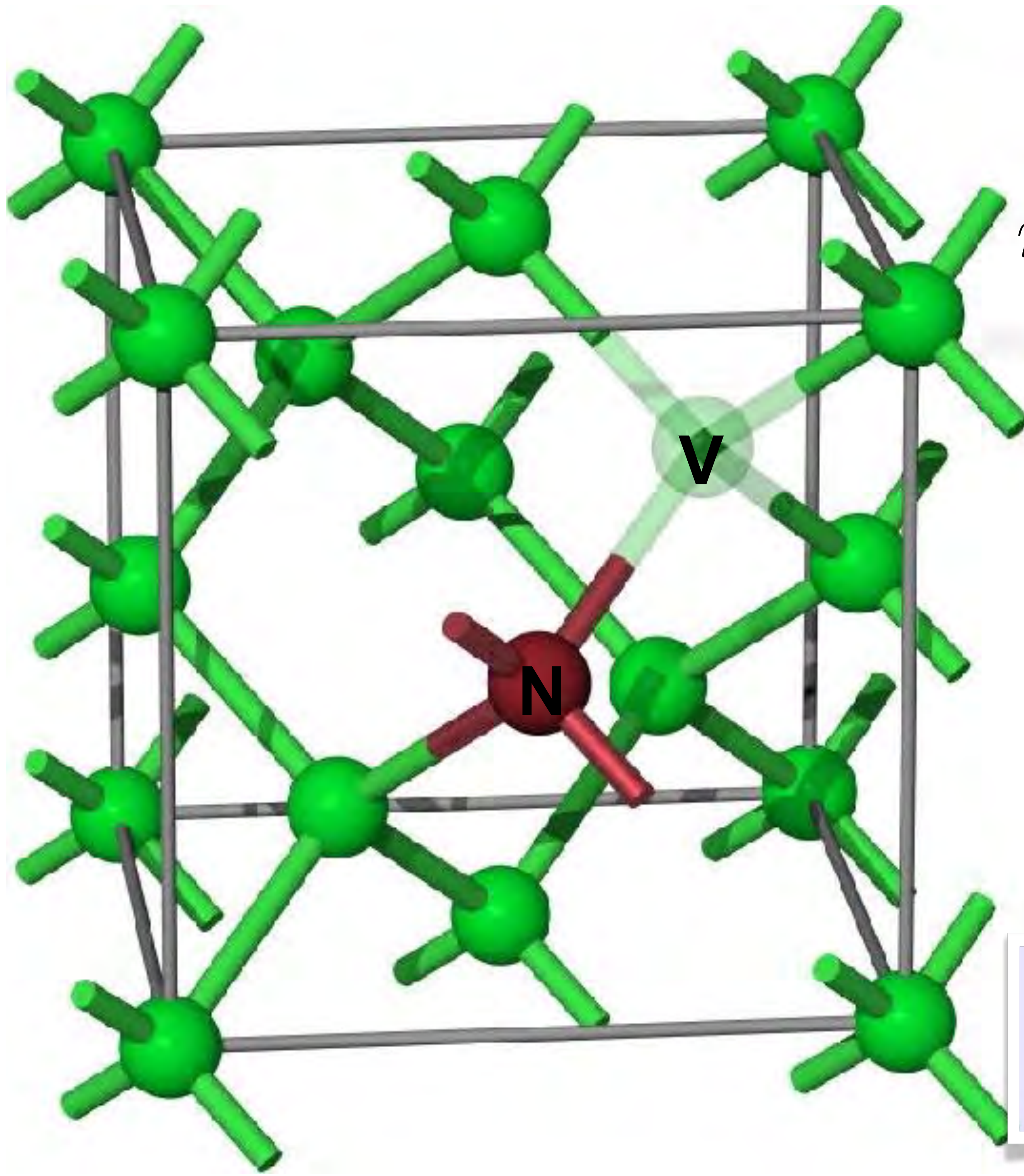


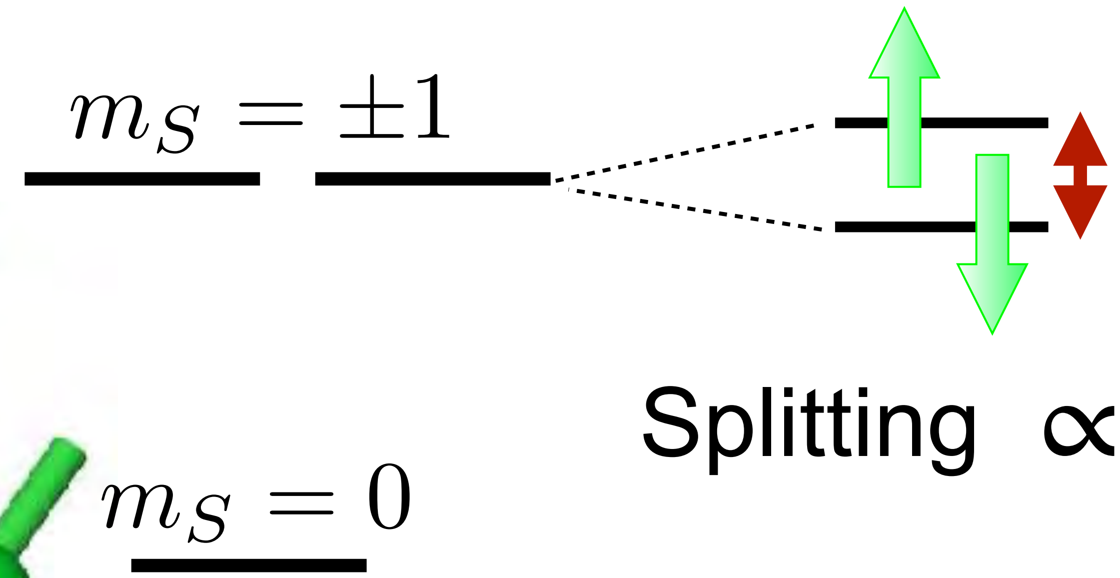
Single Atom Magnetometer



Sensing Magnetic Fields

$\overrightarrow{B}$ is a vector !





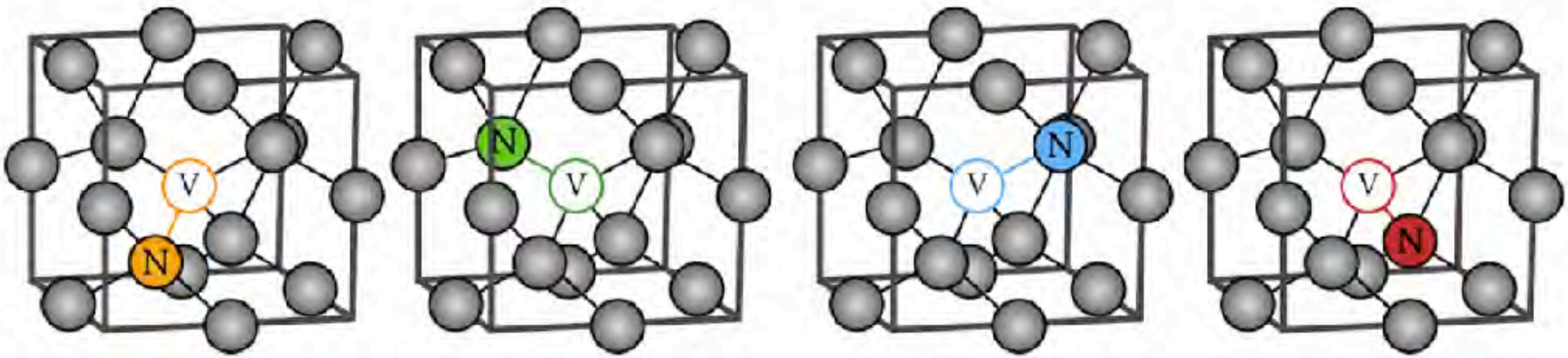
Splitting $\propto B_z$

A single NV measures component || z (NV-axis)

Can we measure all components?

Sensing $\vec{B}$

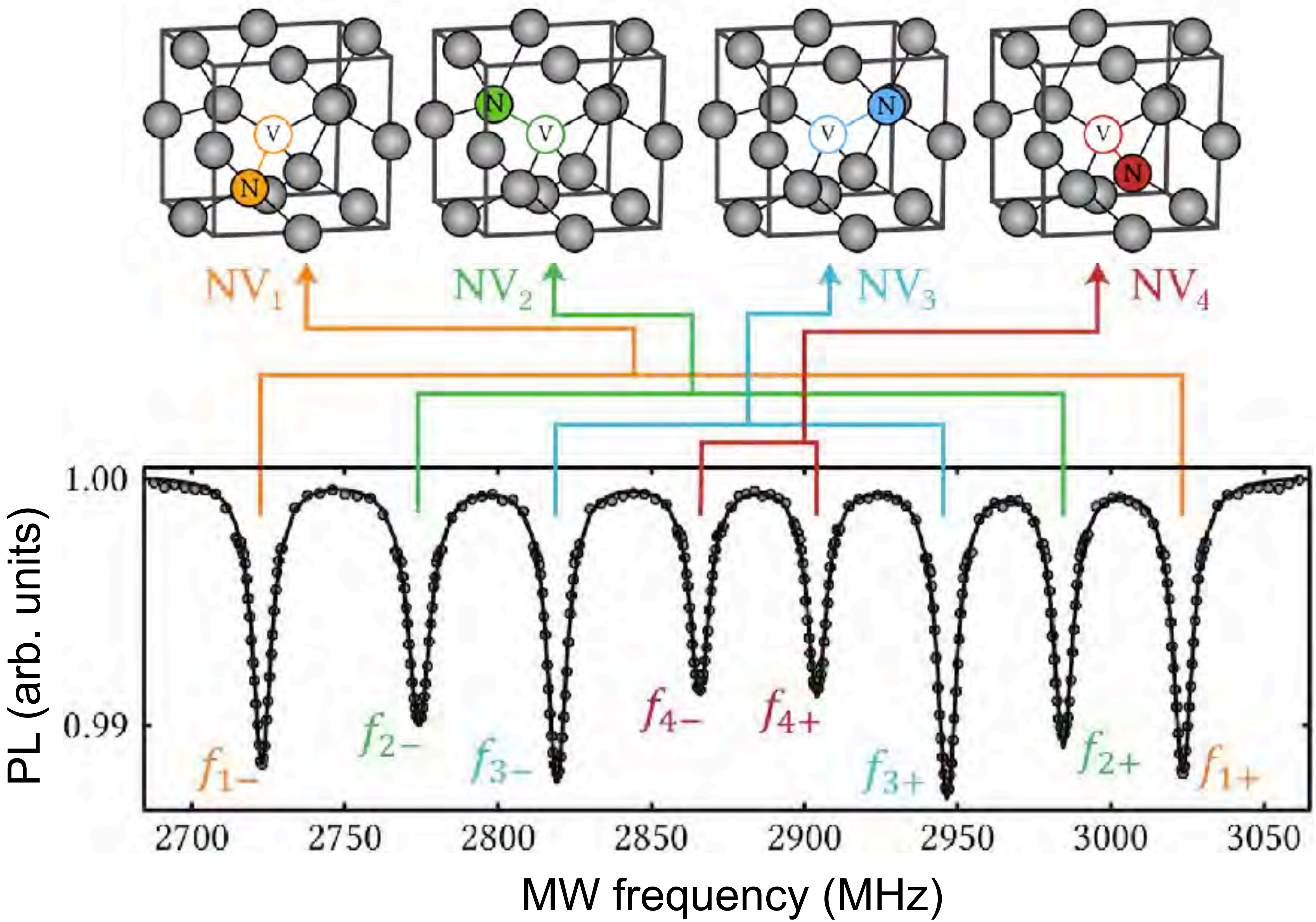
Can we measure all components?



Tetrahedral symmetry around every atom

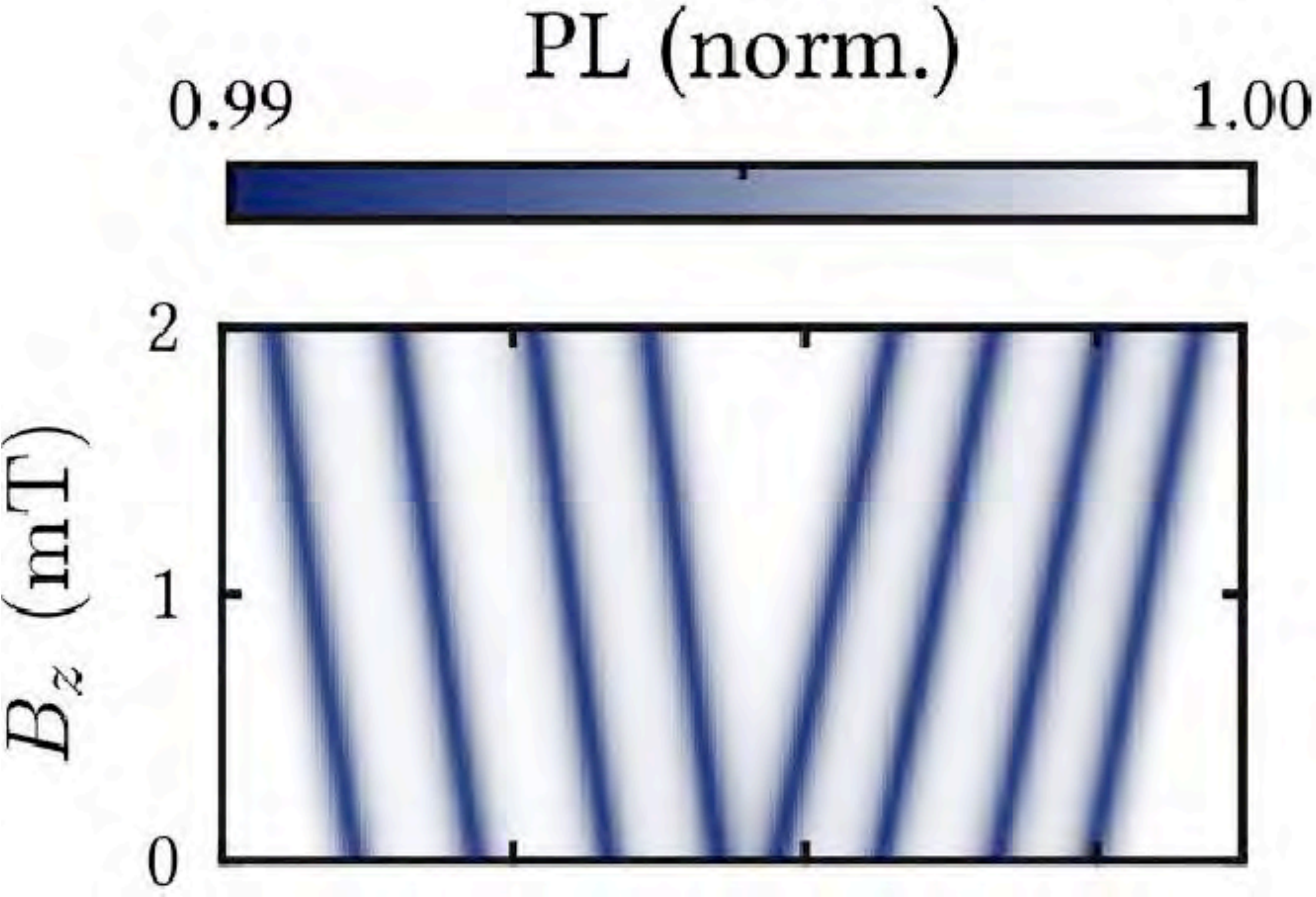
4 equivalent orientations in an ideal crystal

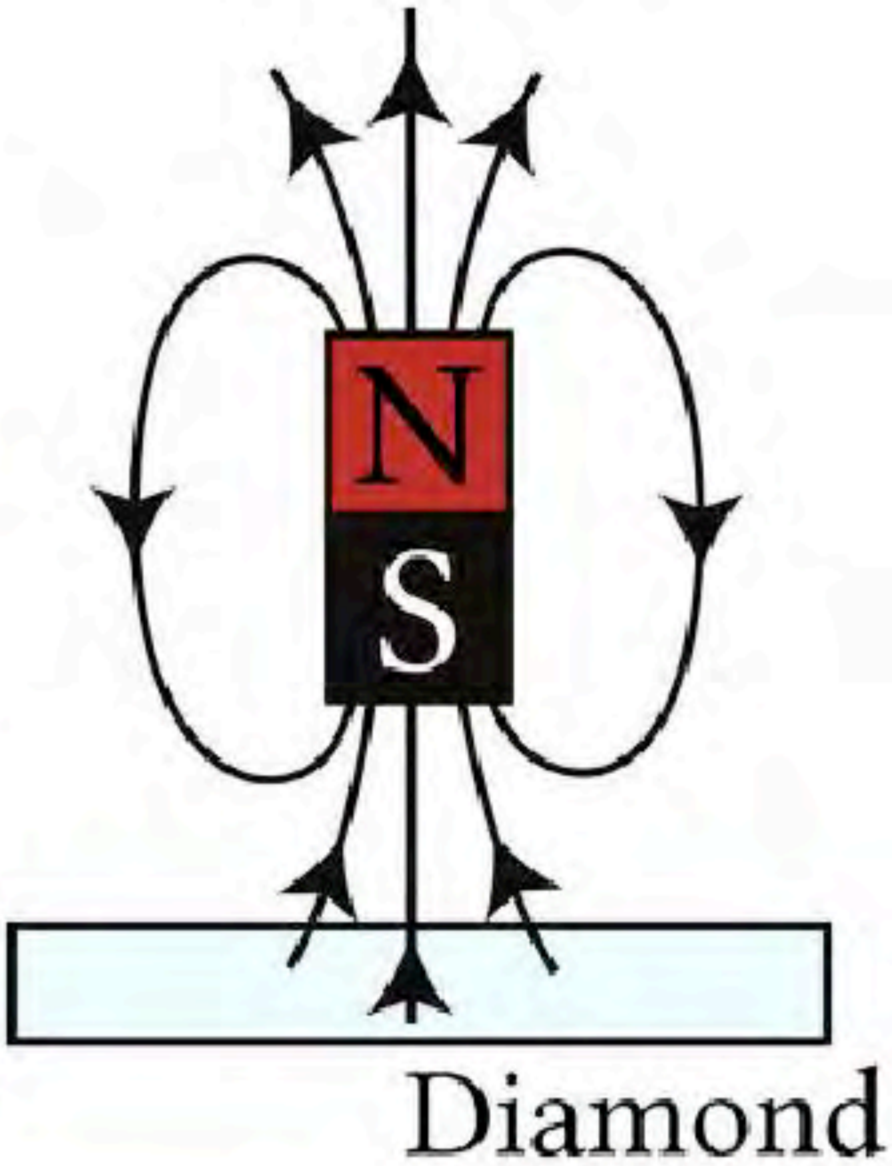
Sensing $\vec{B}$



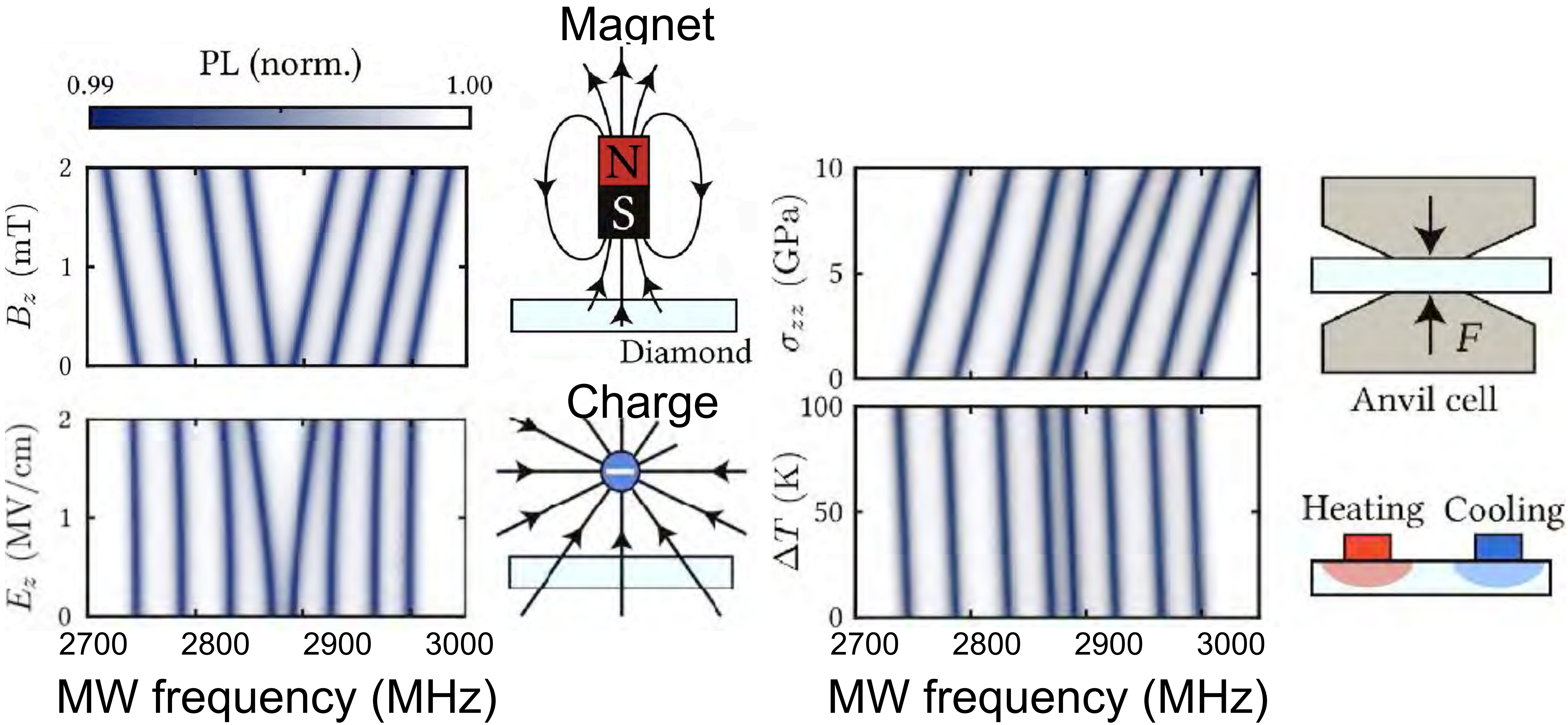
J. Appl. Phys. 130, 150902 (2021).

Variation with |B|





Sensing Modalities



J. Appl. Phys. 130, 150902 (2021).

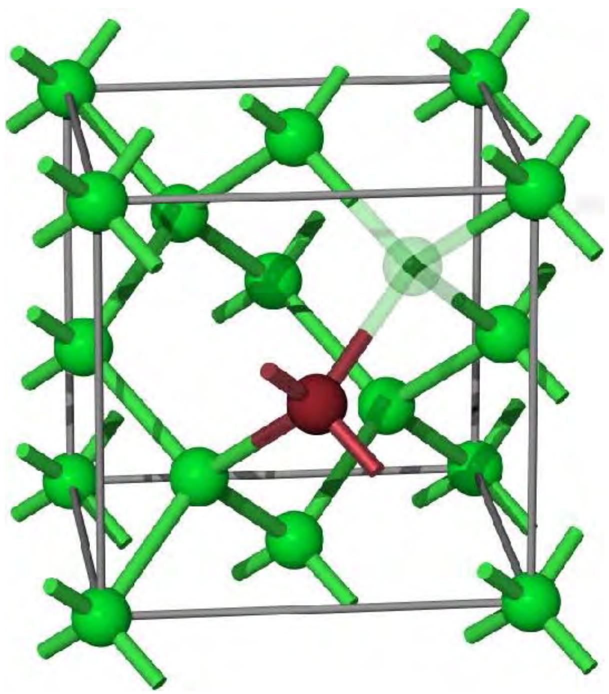
Sensing Magnetic Fields

$\vec{B}$ is a vector !

3 Amplitude components

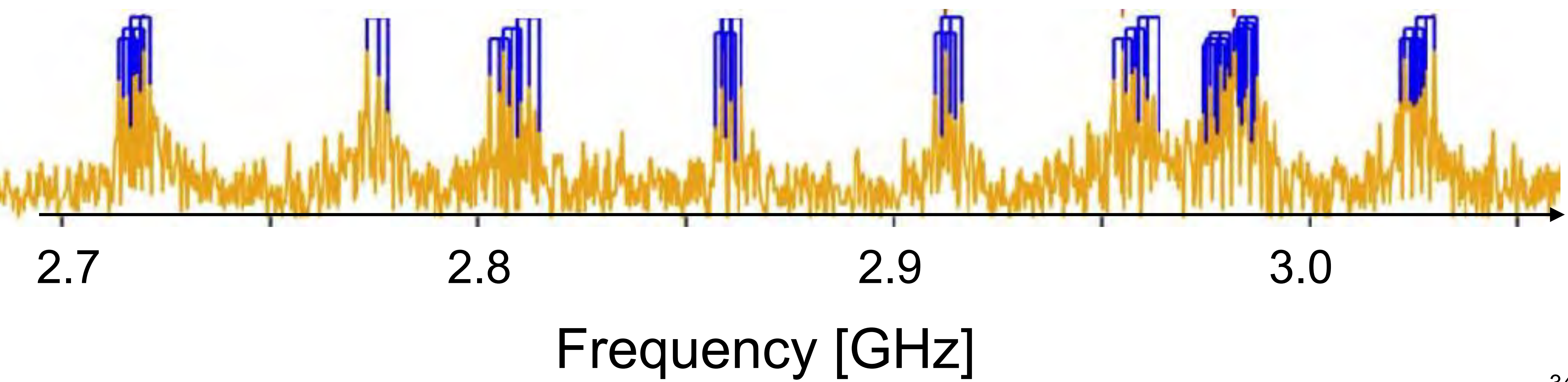
Frequency $\quad \vec{B}(t) = \vec{B}(\omega t + \varphi)$

Phase



Can we measure all these quantities with NVs?

Use multiple NVs in a sample to measure components



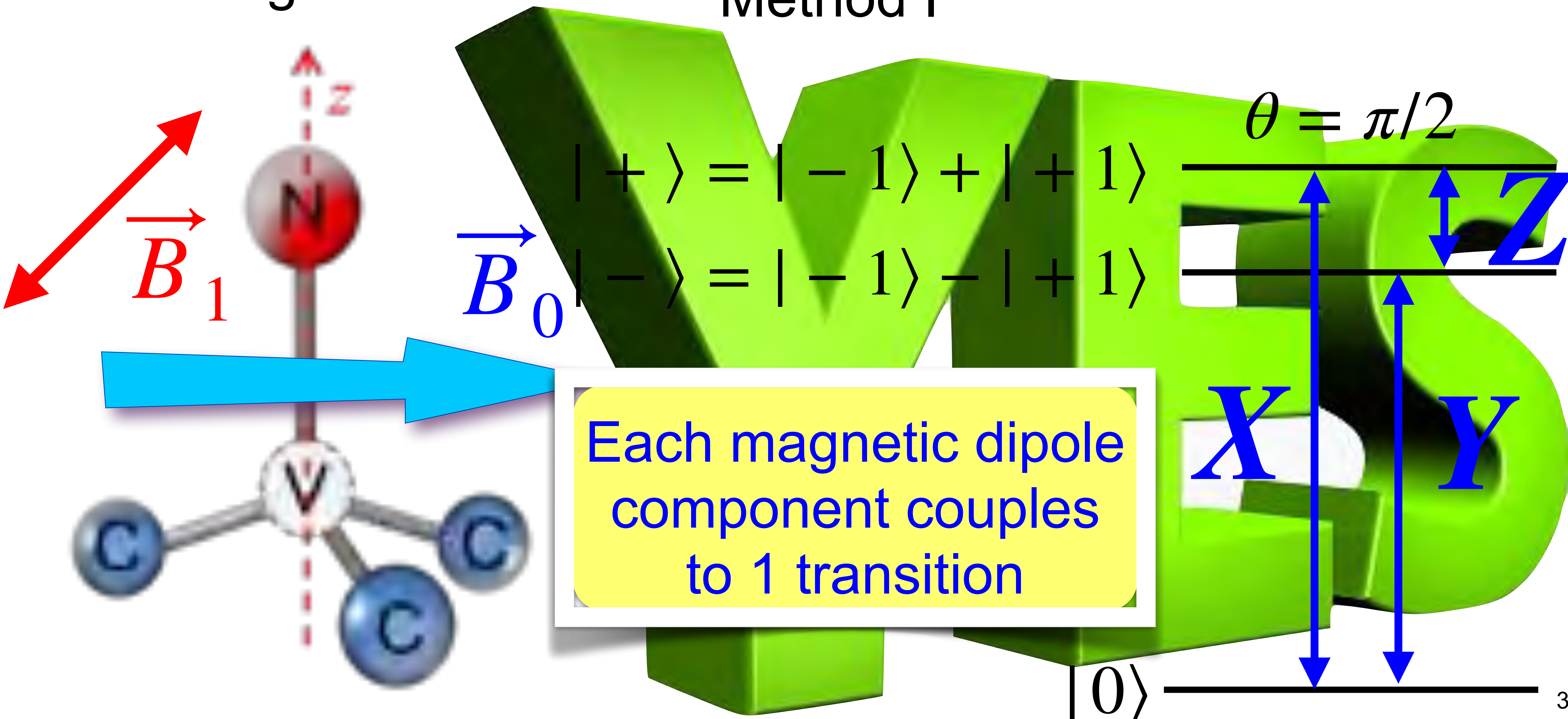
Sensing Magnetic Fields

$\vec{B}$ is a vector !

Can we measure all these quantities with NVs?

Can we measure all these quantities with a single NV?

Method I

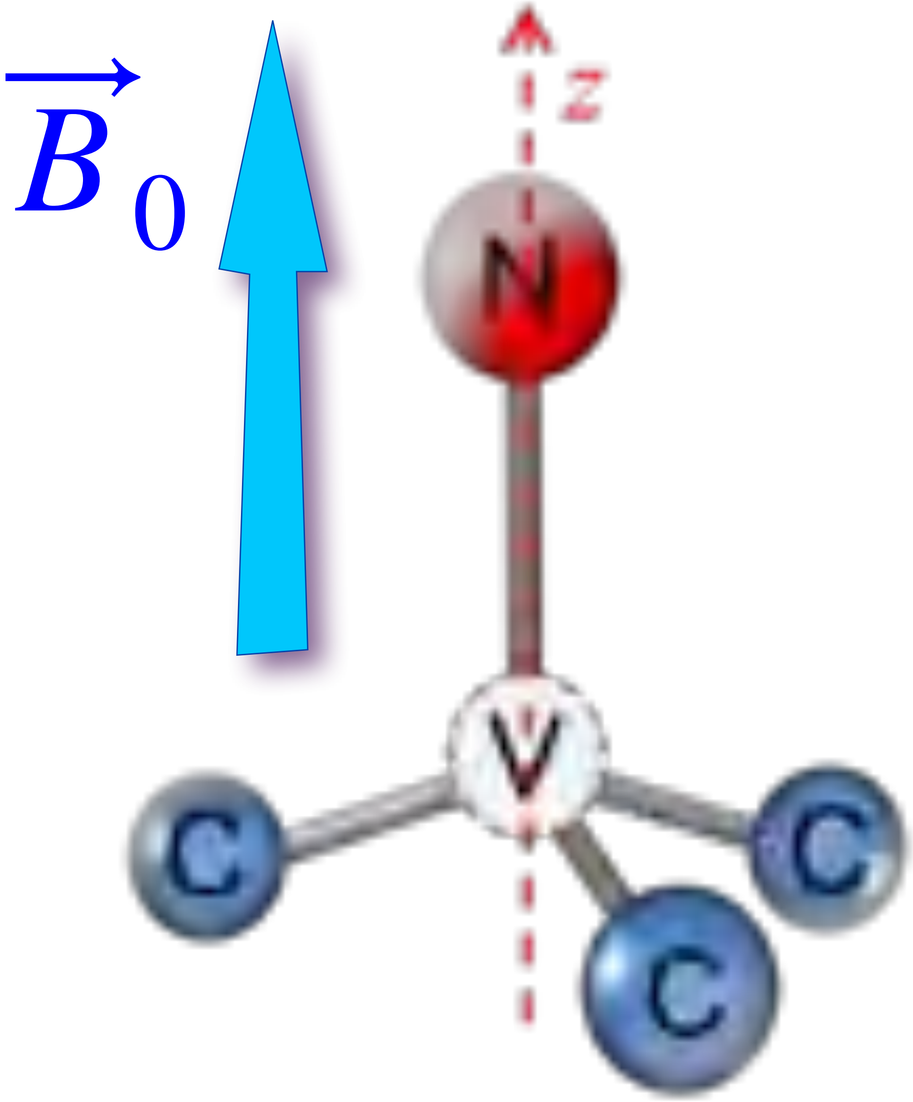


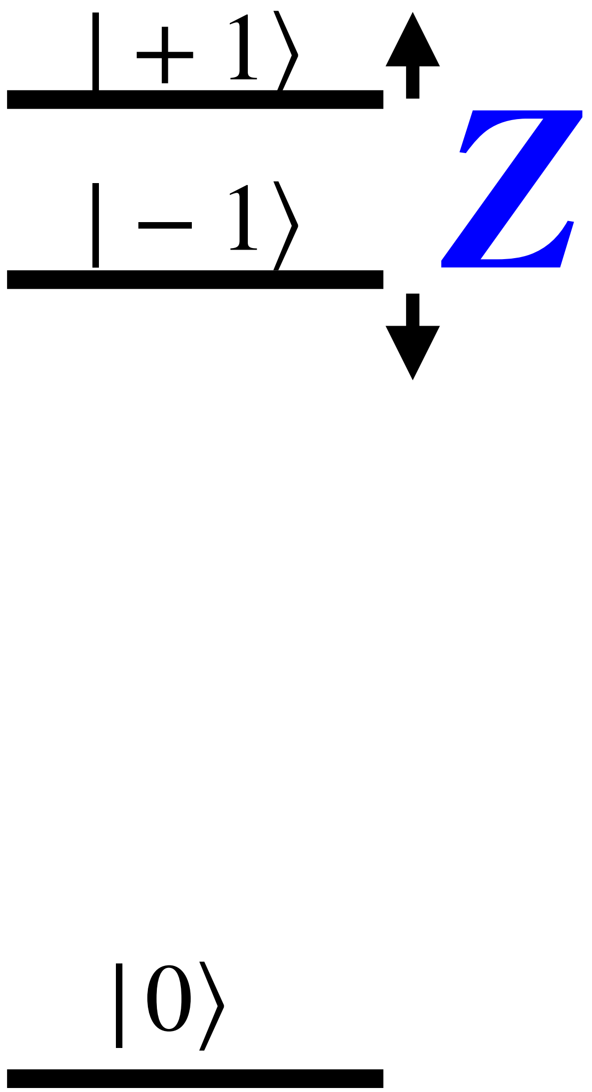
Vector Sensing

$\vec{B}$ is a vector !

Can we measure all these quantities with single NVs?

Method II





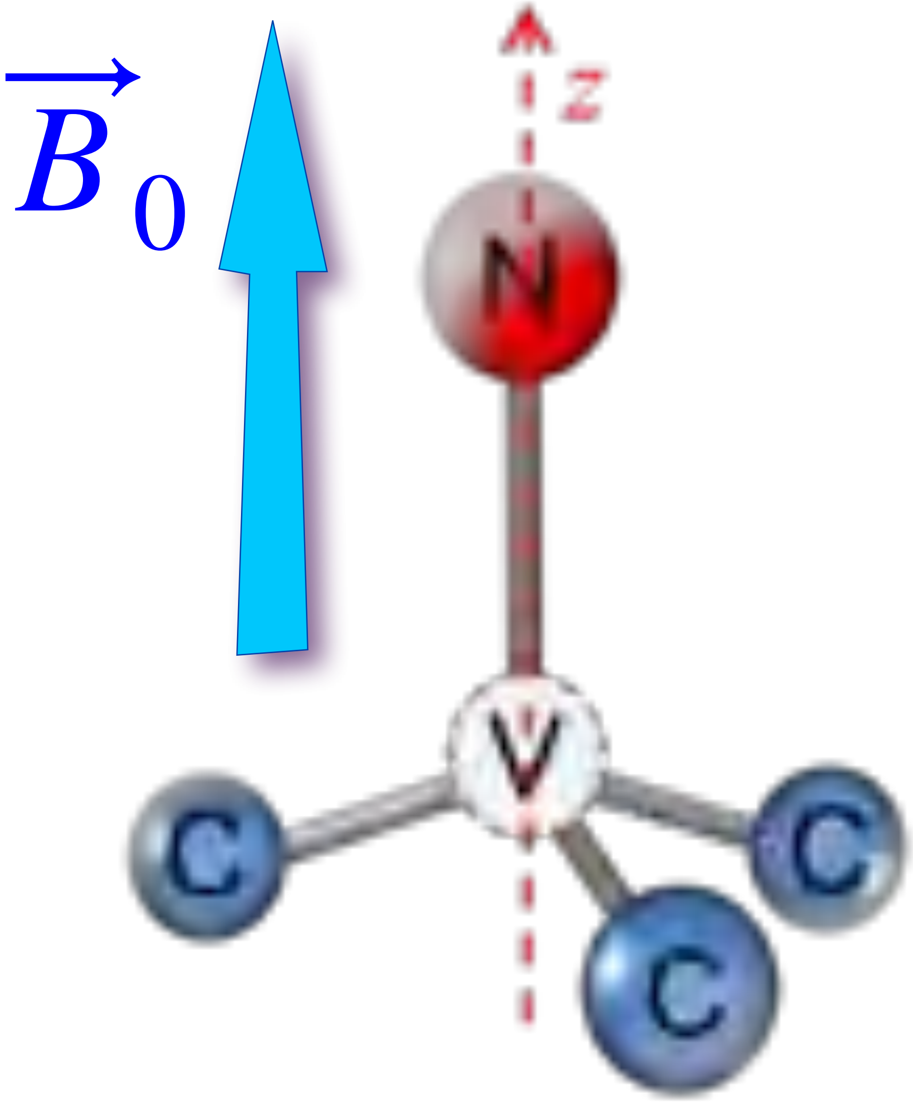
New Journal of Physics 22, 103065 (2020).

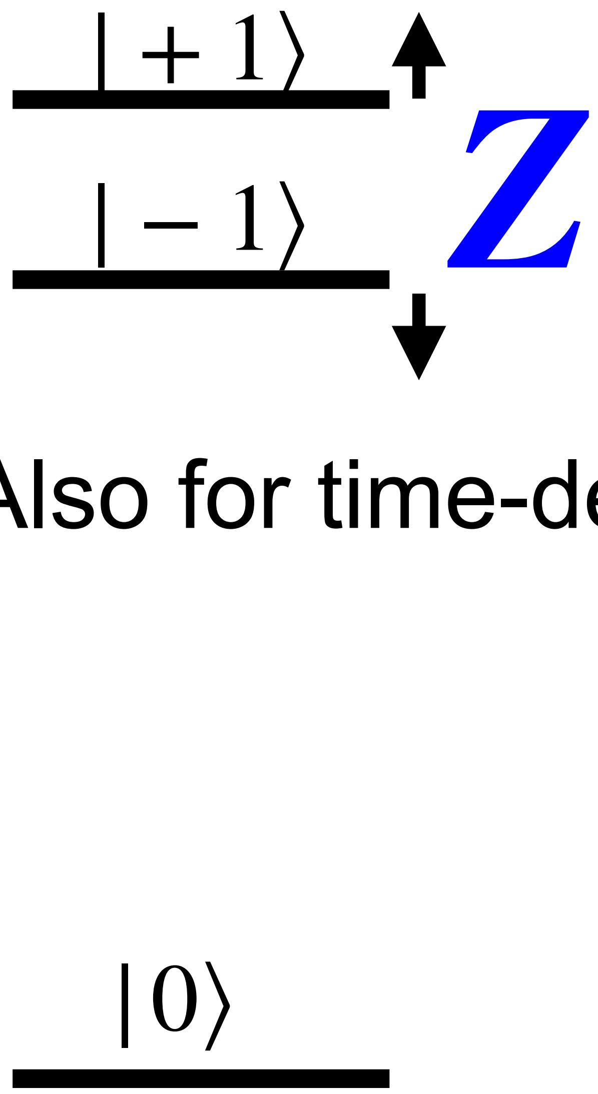
Vector Sensing: AC and DC

$\vec{B}$ is a vector !

Can we measure all these quantities with single NVs?

Method II

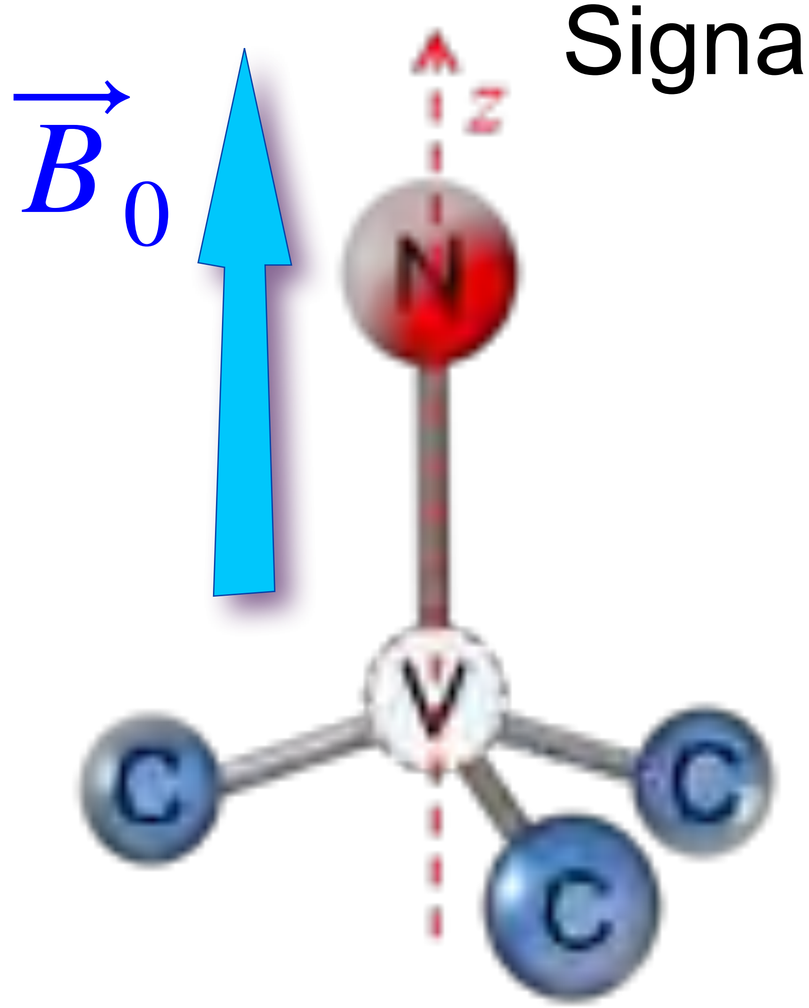


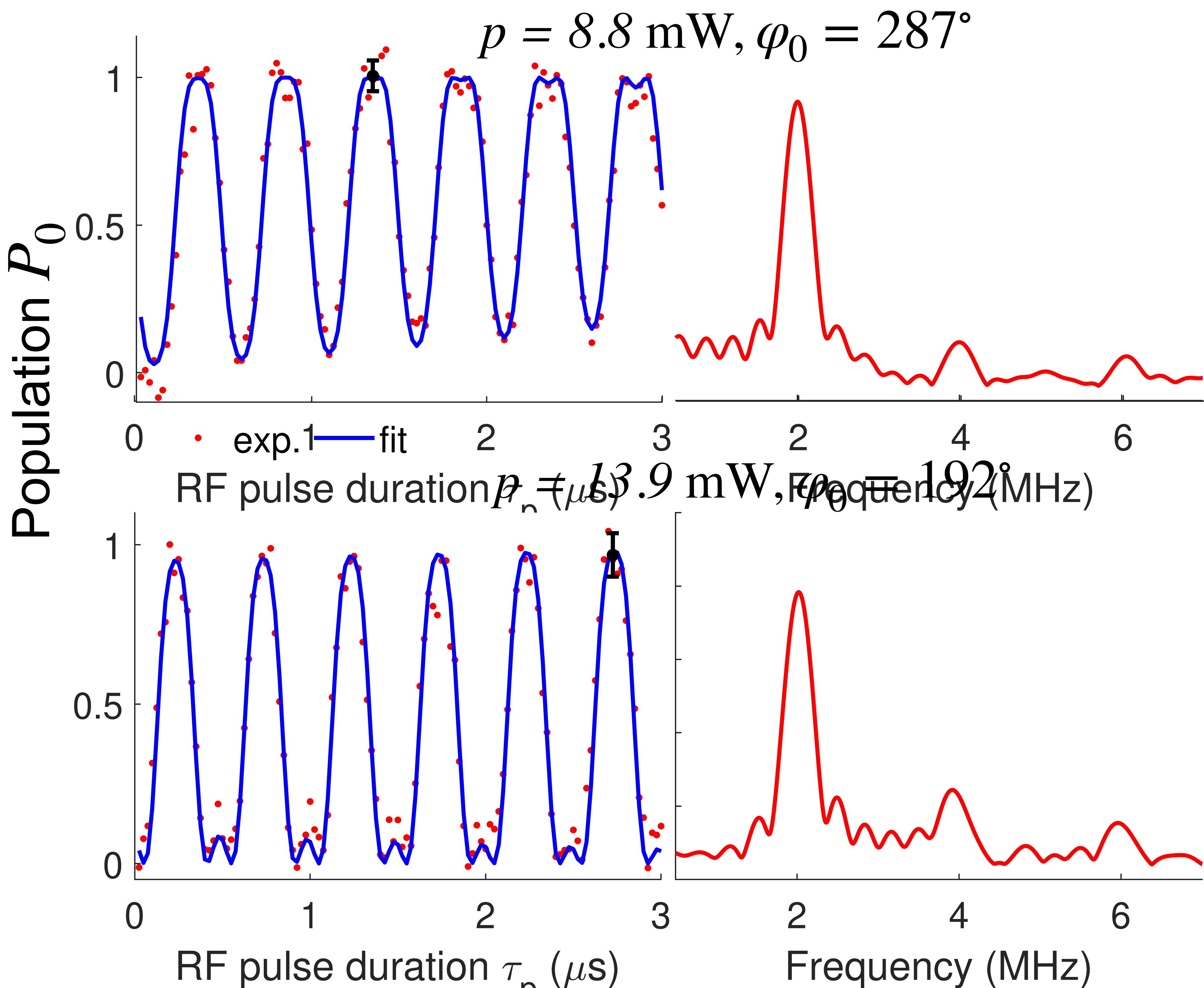


Also for time-dependent signals!

Vector Sensing: AC and DC

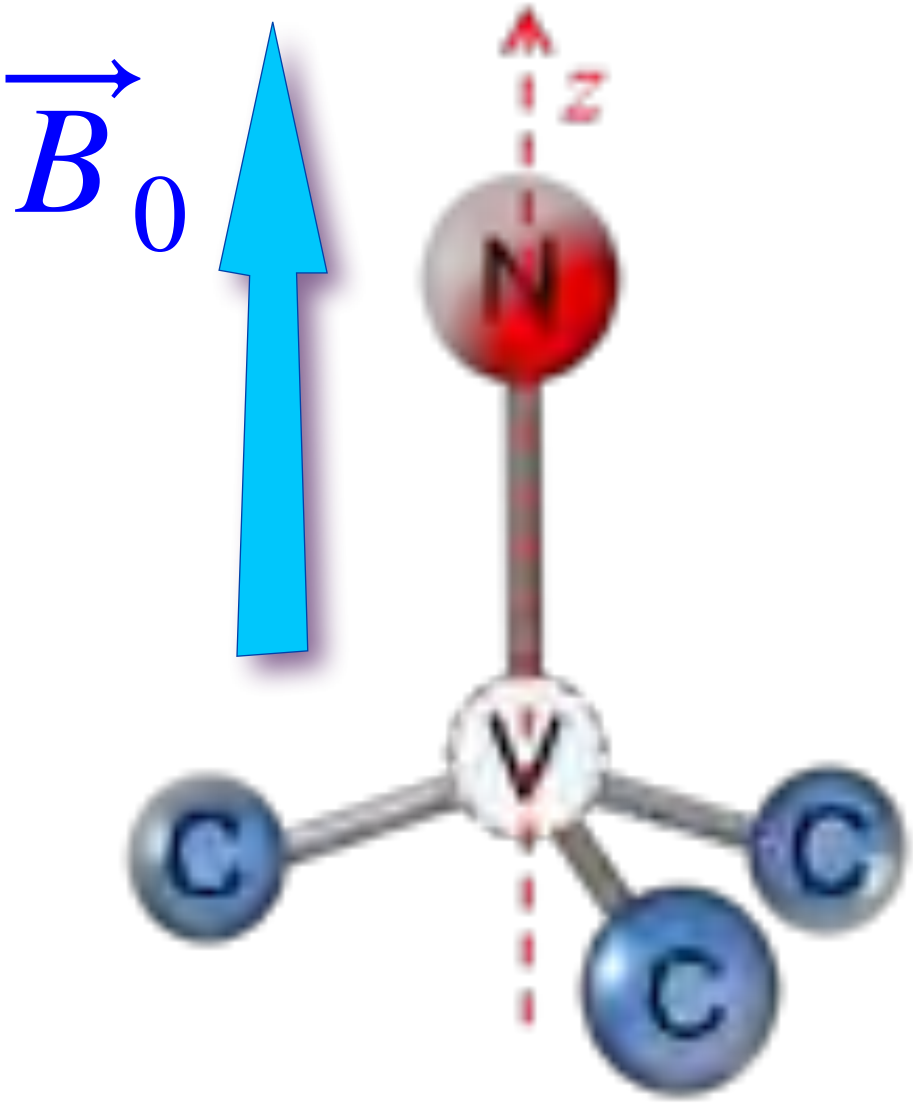
Signal $\propto \sin(\omega t + \varphi)$; $\omega/2\pi = 2$ MHz

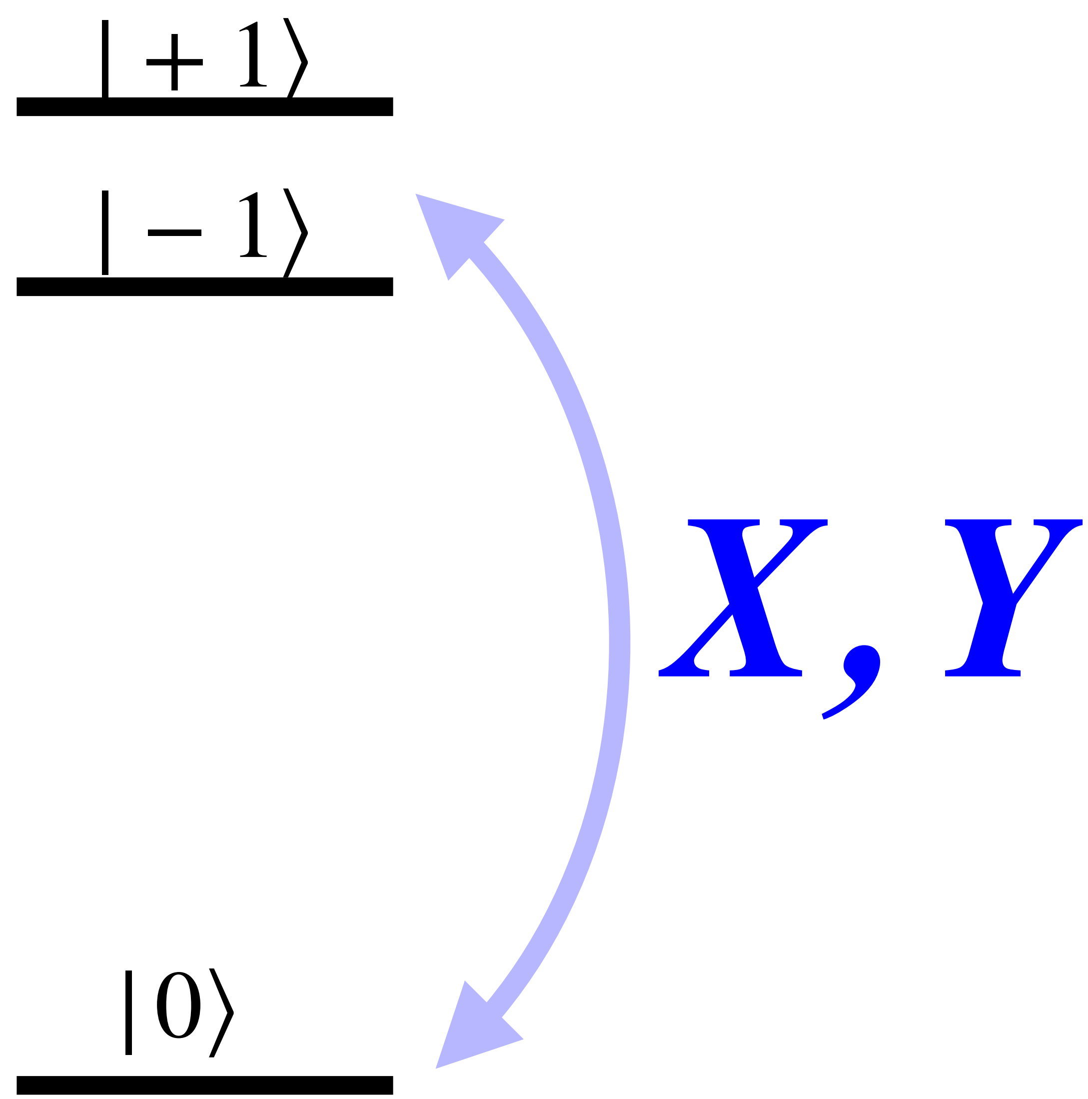




Vector Sensing: X, Y

Transverse components?



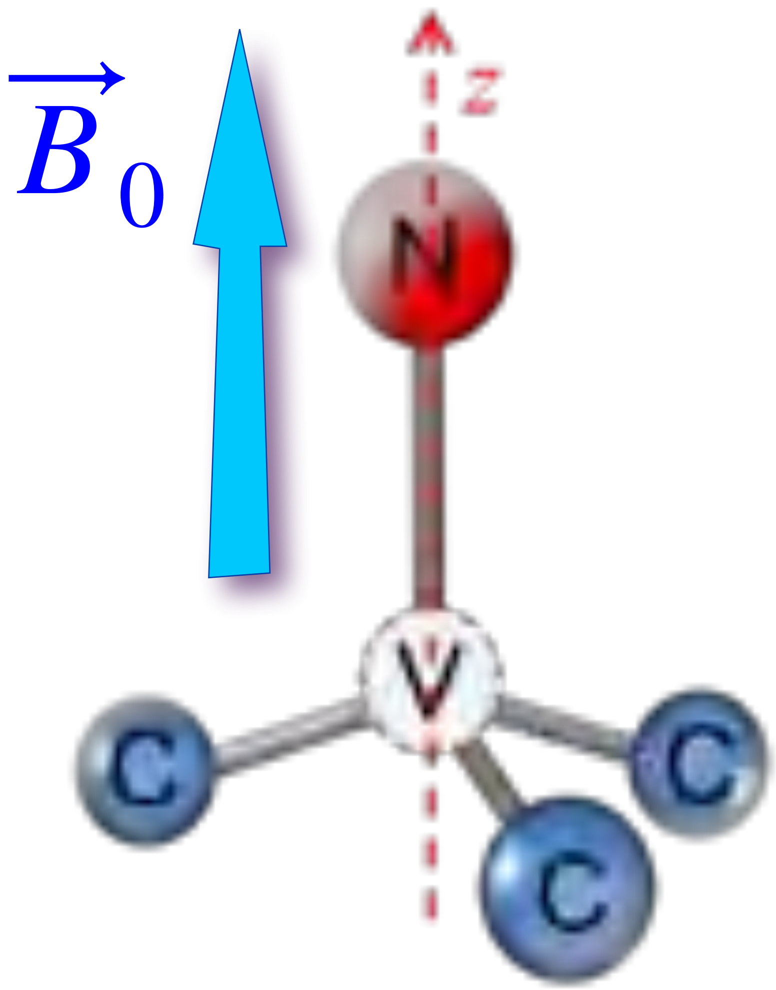


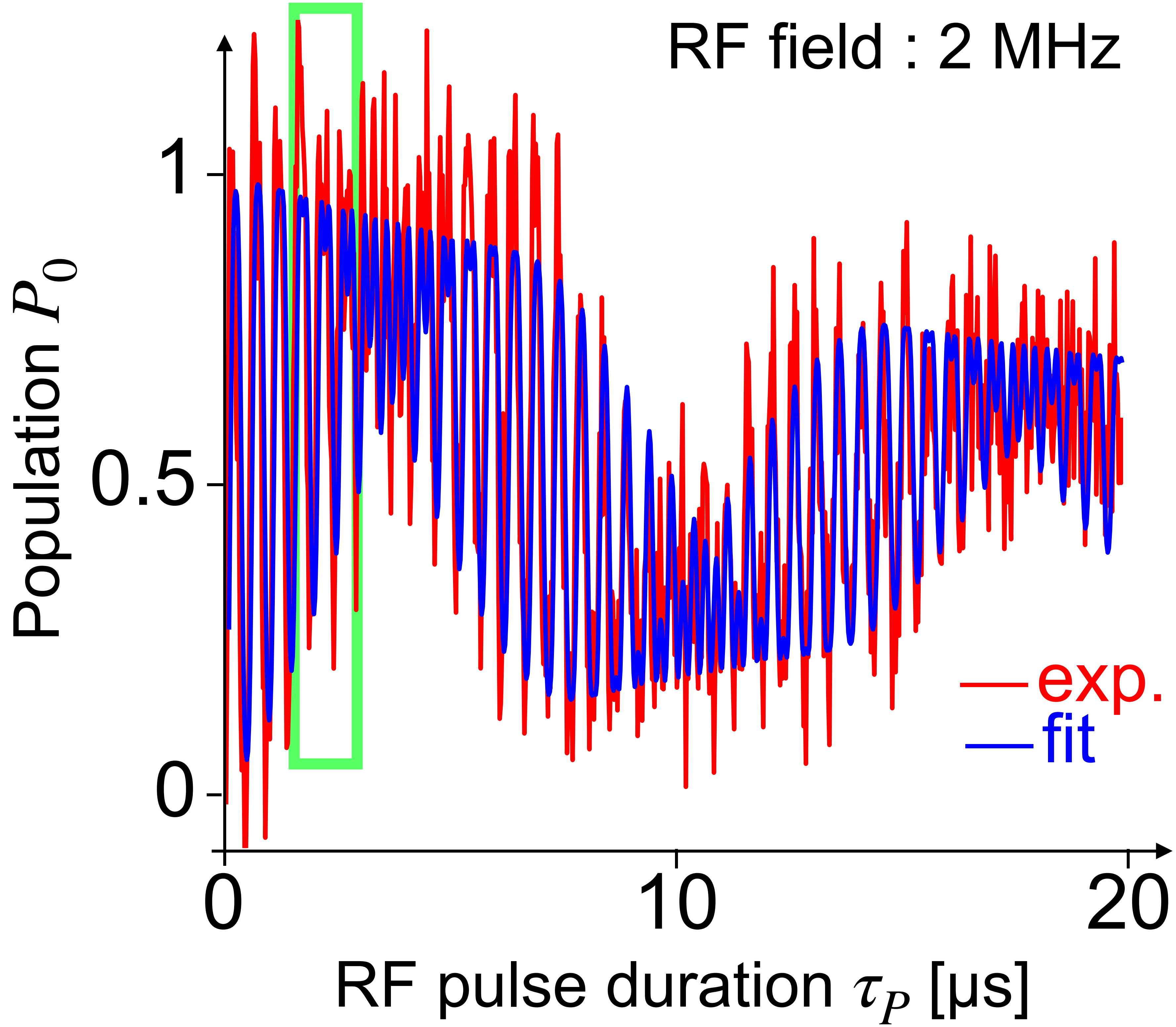
Nonsecular

→ Observable on longer timescales!

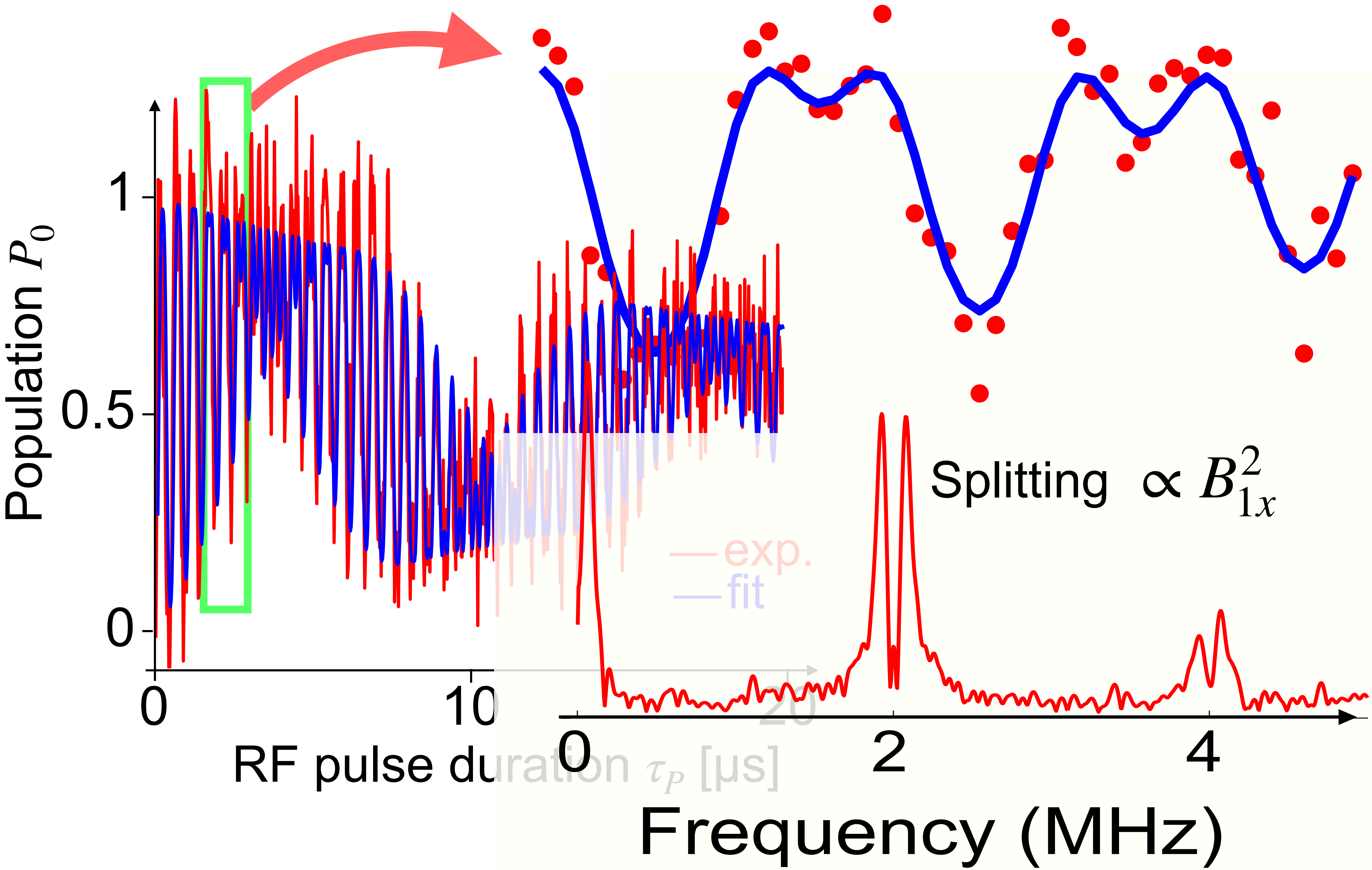
~Bloch-Sigert shift with time resolution

Vector Sensing: X, Y, Z



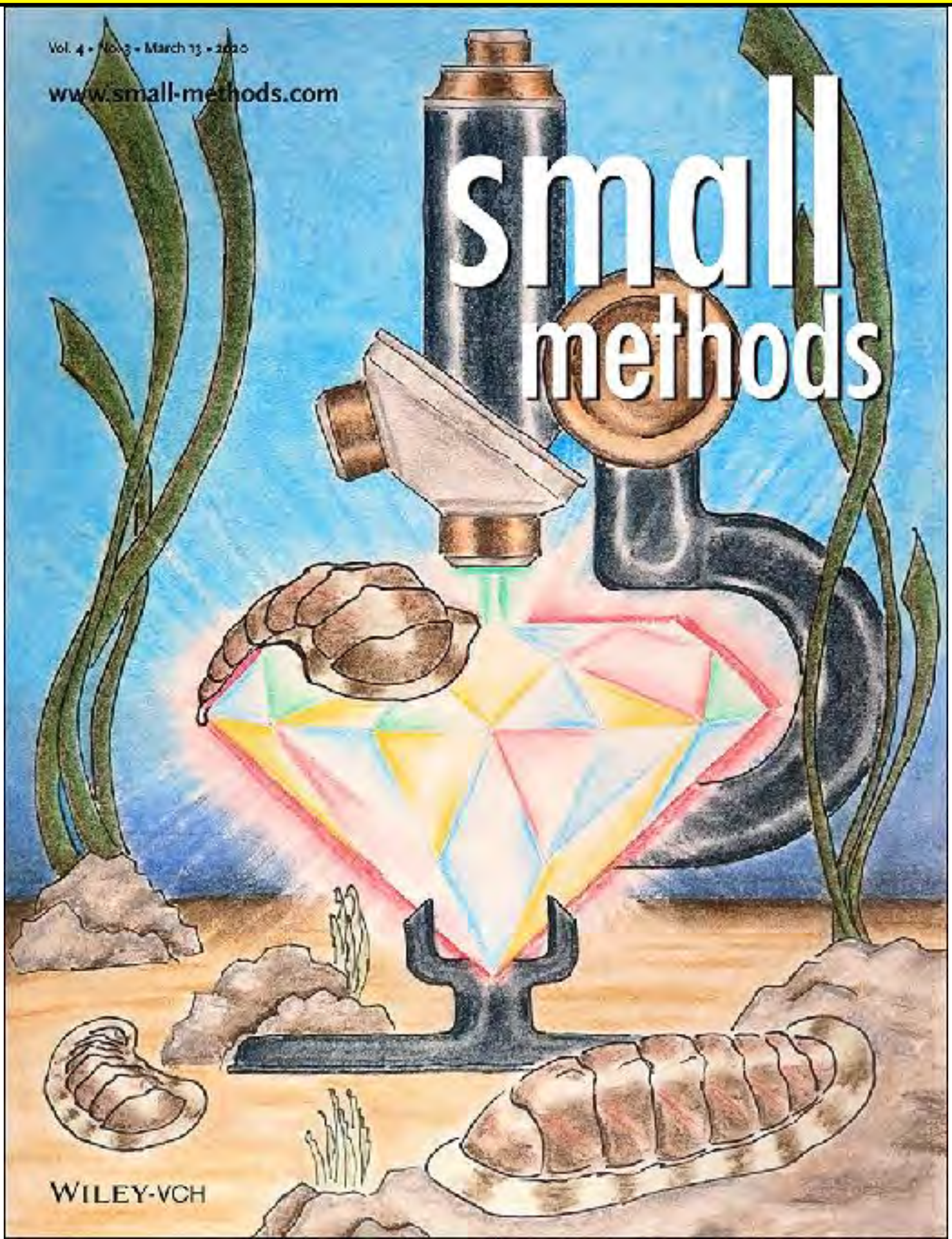


Vector Sensing: AC and DC

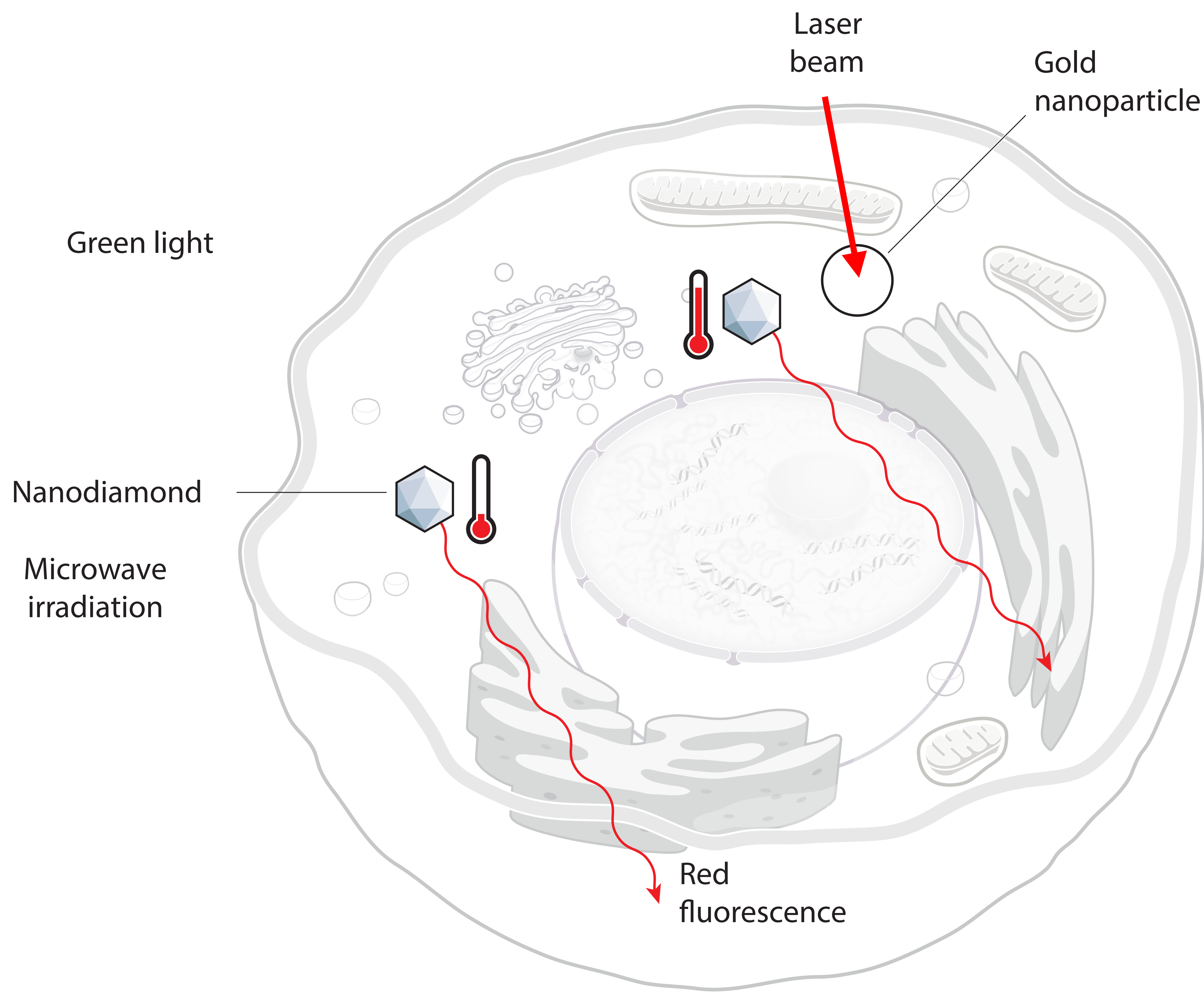


PR Research 5, L022026 (2023).

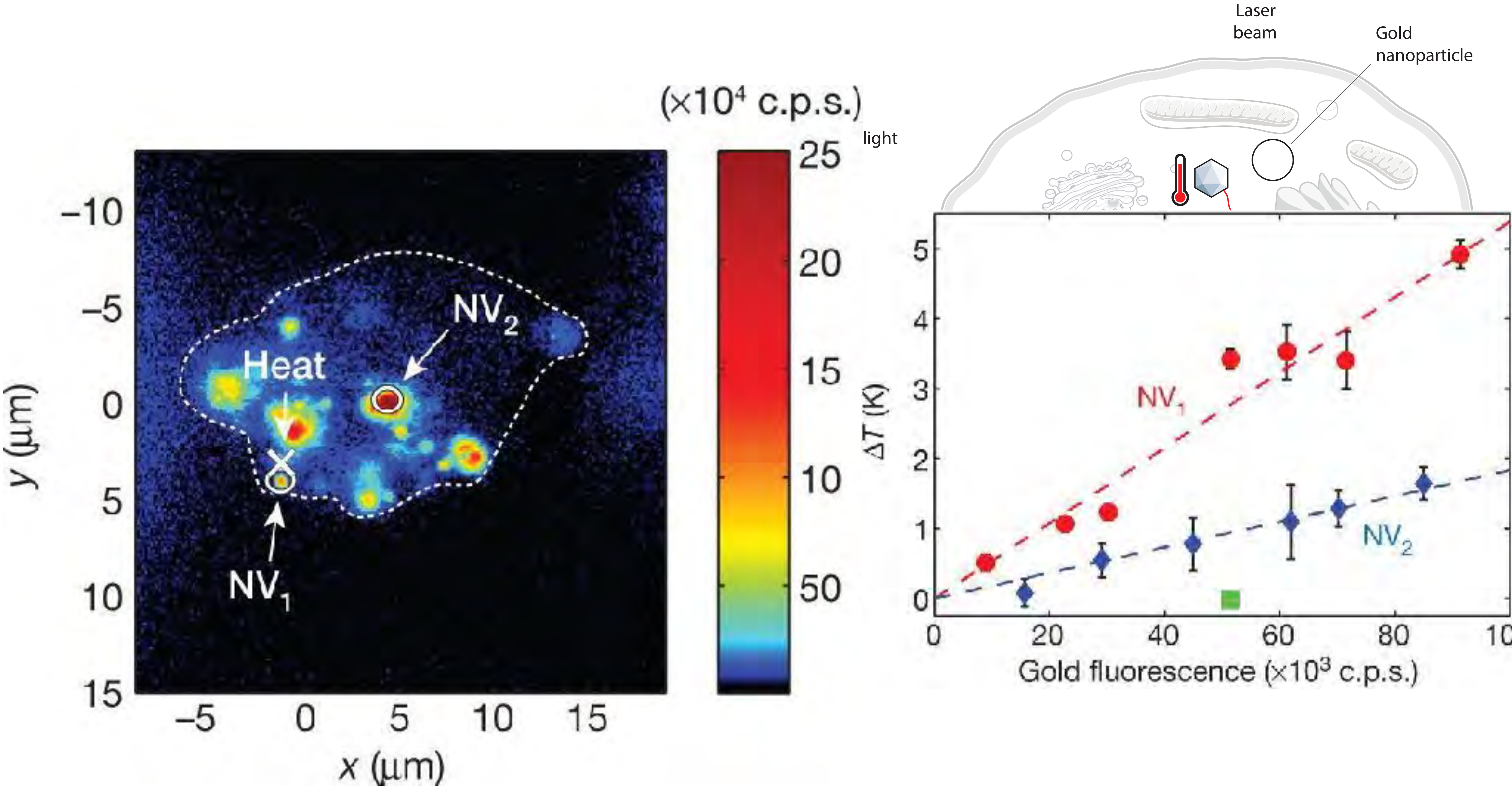
Sensing Biological Systems



Nanoscale Thermometry

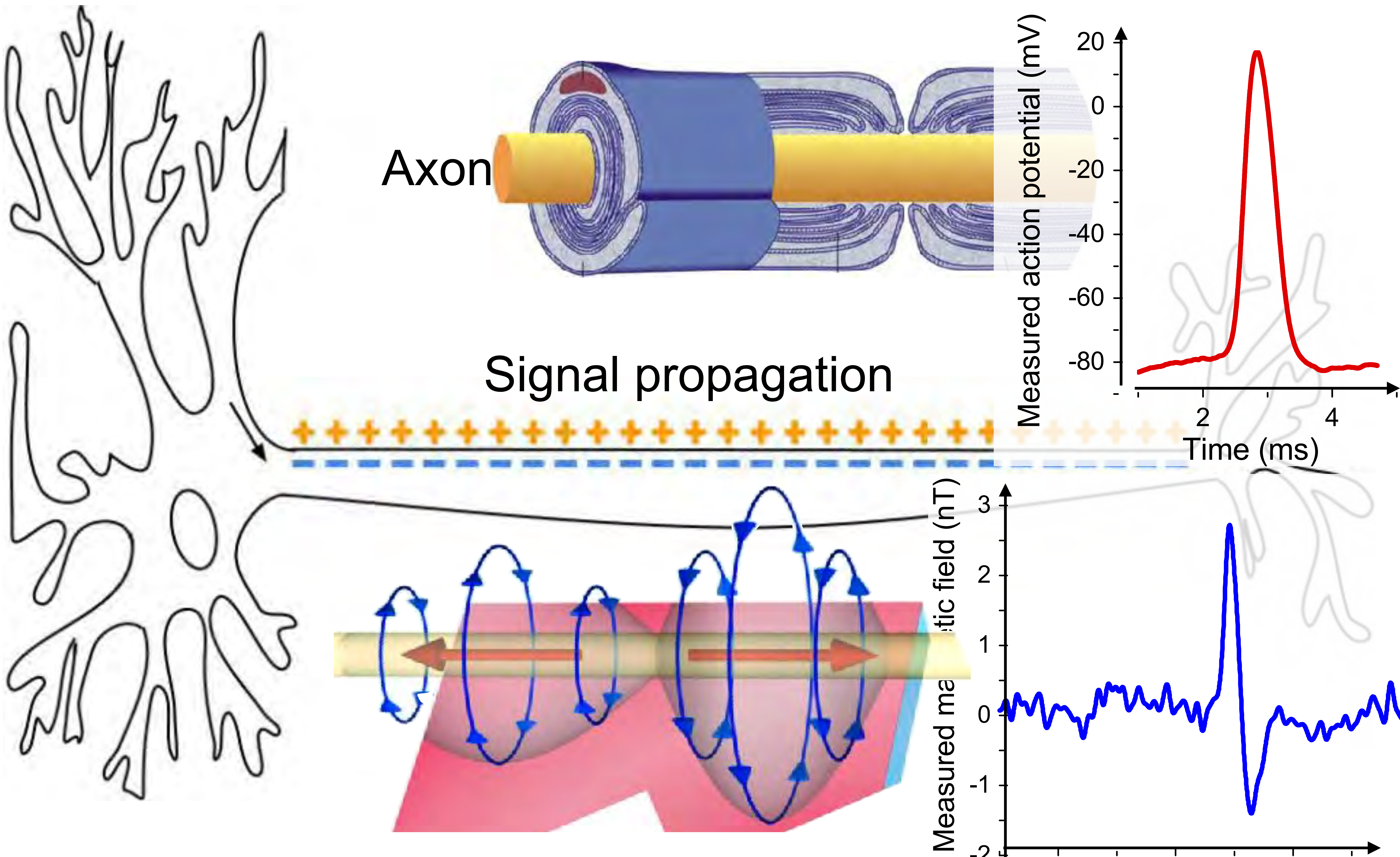


Nanoscale Thermometry



G. Kucsko et al., Nature 500, 54-58 (2013).

Sensing Biological Systems



Barry et al., Proc Natl Acad. Sci. USA 113, 14133-14138 (2016).

Future directions:

- Spatial resolution
- Other samples
- e.g. axons of mammalian neurons

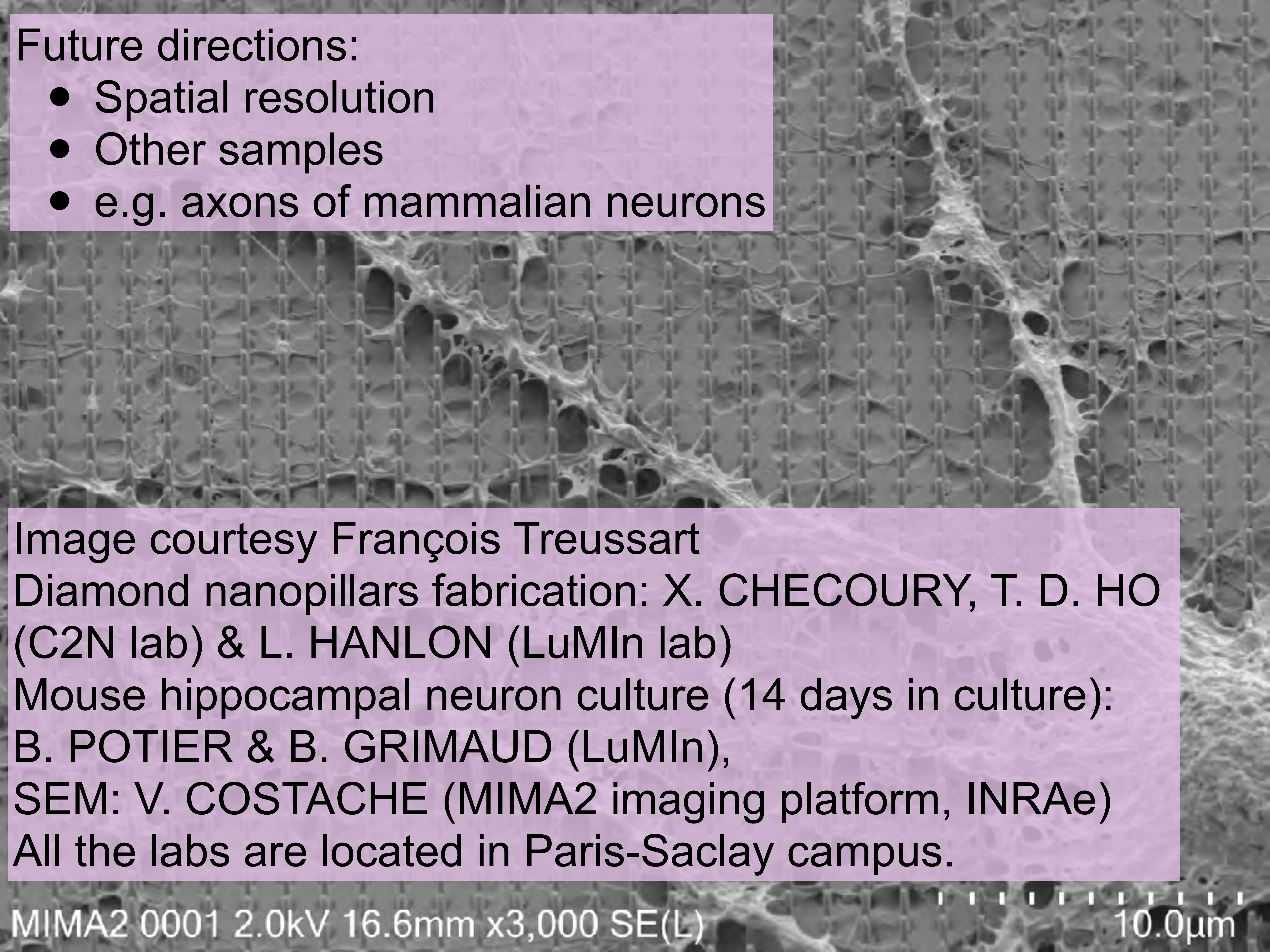


Image courtesy François Treussart
Diamond nanopillars fabrication: X. CHECOURY, T. D. HO (C2N lab) & L. HANLON (LuMIn lab)
Mouse hippocampal neuron culture (14 days in culture): B. POTIER & B. GRIMAUD (LuMIn),
SEM: V. COSTACHE (MIMA2 imaging platform, INRAe)
All the labs are located in Paris-Saclay campus.